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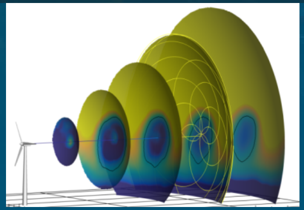
Sandia National Laboratories

National Rotor Testbed Strain Gauge Calibration and Compensation Process



PRESENTED BY

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National Rotor Testbed (NRT)

- Sandia designed blades retrofitted to a 200 kW variable speed, variable pitch Vestas V27
- NRT Goals
  - Show scaled wake design through blade strain measurements
  - Conduct wind turbine wake experiments relevant to megawatt scale turbines
  - Validate wind turbine models with an open source, well-documented, and highly instrumented wind turbine

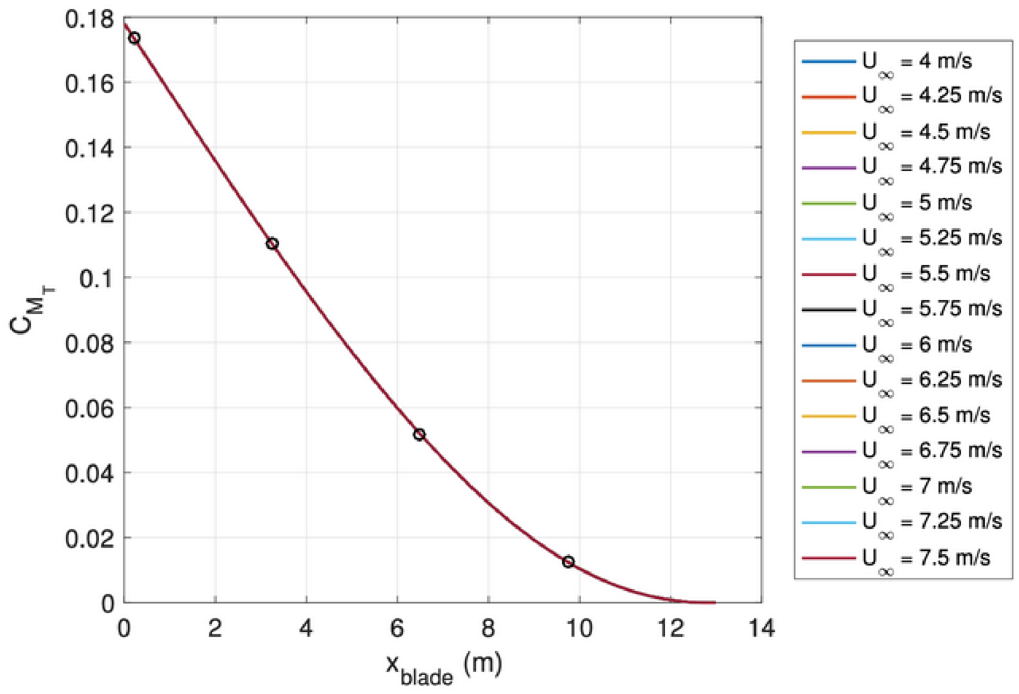
Design Documentation on GitHub

NRT Scaled Wake Design

- Design NRT blades to create scaled wake of GE 1.5sle
- Scaled wake means equal normalized axial velocity at rotor plane
- Following quantities are equal for NRT and GE 1.5 sle turbines in region 2
  - $\frac{u}{U_\infty}\left(\frac{r}{R}\right)$ normalized axial velocity across the rotor normalized radius
  - $a\left(\frac{r}{R}\right)$ axial induction across the rotor normalized radius
  - $\Gamma'\left(\frac{r}{R}\right)$ dimensionless circulation across the rotor normalized radius
  - C_T thrust coefficient
  - λ tip-speed-ratio

NRT Design Verification Experiment

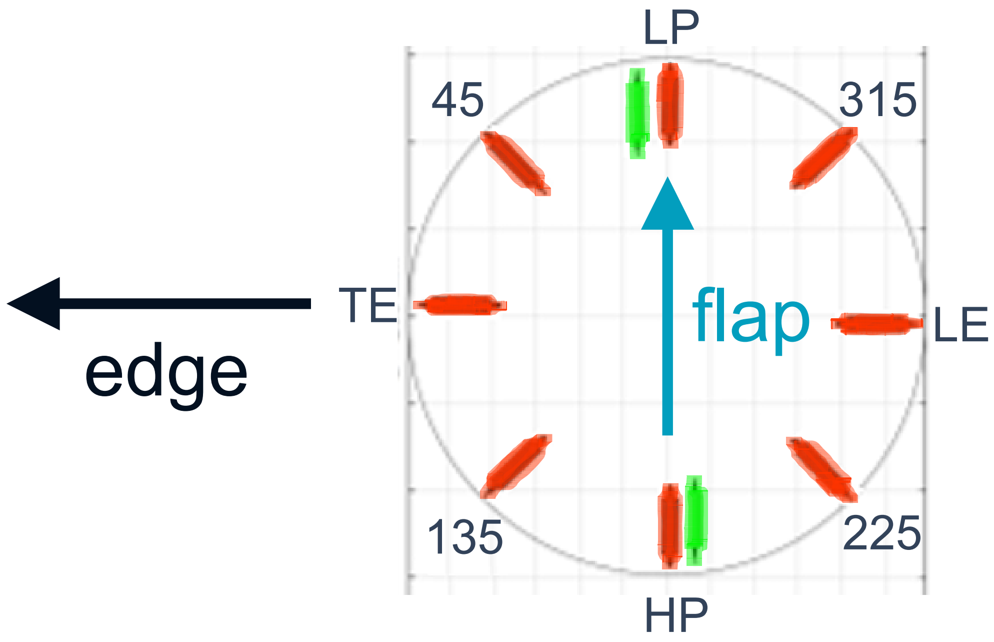
- Ideal measurements
  - use aero measurements on blade to directly measure circulation
  - SpinnerLidar to measure wake profile for comparison with GE 1.5 sle
- Project constraints (timeline and cost) required use of distributed strain gauges
  - Use strain gauges to calculate aerodynamic loads on blades
  - Remove effect of thermal strain, centripetal acceleration, and cross-talk
  - Compare measured aerodynamic bending moment coefficients to NRT design
  - Tune collective pitch and torque constant if experiment doesn't match design

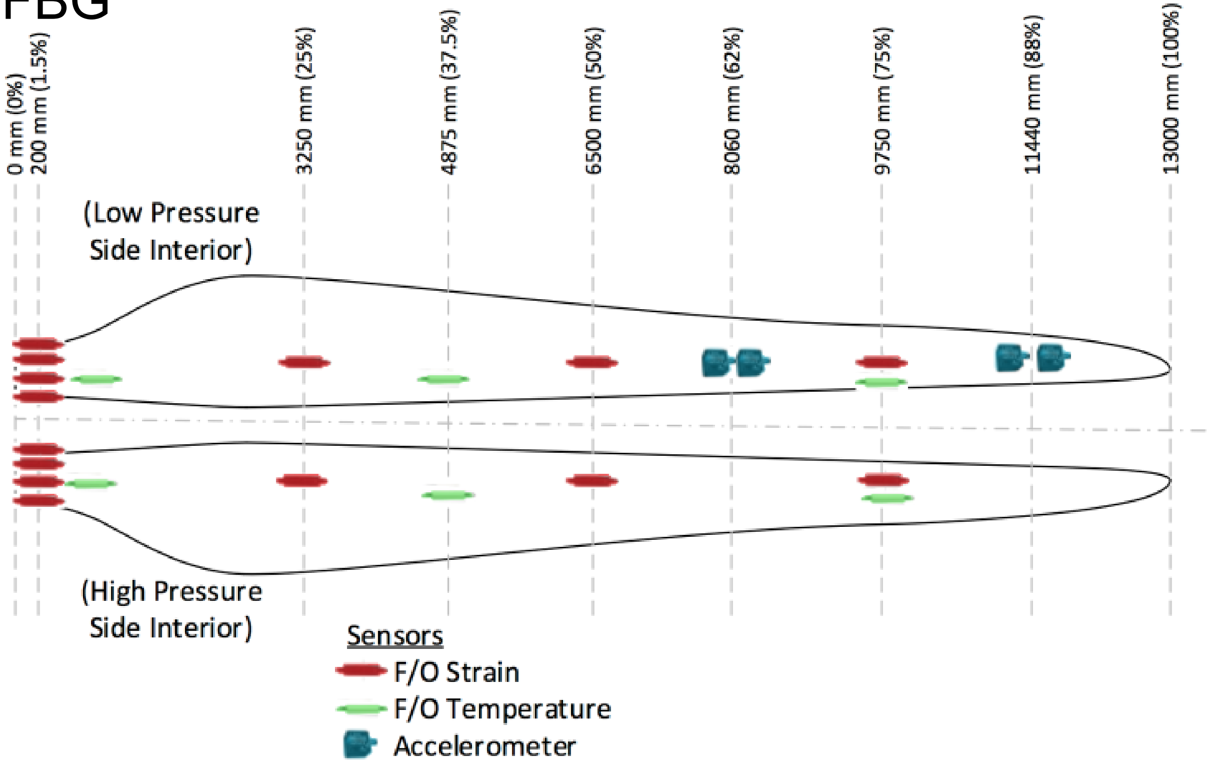


Thrust bending moment coefficients across blade span for NRT design

Instrumentation

- Strain gauges: Micron Optics Fiber Optic OS3200
  - Spaced 45 degrees at root, high/low pressure side outboard
  - Calibrated to measure aerodynamic bending moment
  - Root foil gauges to compare with FBG
- Accelerometers: Silicon Designs 2470
- Blade Temperature: Micron Optics Fiber Optic OS4300
  - Compensate for thermal strain
- All three blades have same sensors





NRT Strain Calibration

0° Pull

60° Pull

90° Pull

NRT Strain Calibration Equations

Stain temperature compensation

$$strain = CTE \times temp + Off_{temp}$$

Calculate coefficients by fitting moments from each pull to strain data

$$\begin{Bmatrix} s_{hp} - s_{lp} \\ s_{le} - s_{te} \end{Bmatrix} = \begin{bmatrix} A_{0,flap} & A_{90,flap} \\ A_{0,edge} & A_{90,edge} \end{bmatrix} \begin{Bmatrix} M_0 \\ M_{90} \end{Bmatrix} + \begin{Bmatrix} B_{flap} \\ B_{edge} \end{Bmatrix}$$

Model fitted to interpolate the cross-talk moment component across the strain range so that points match across both pull directions

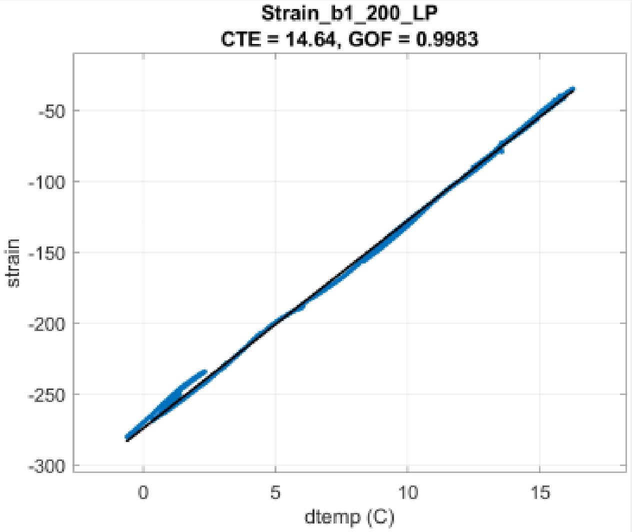
$$\begin{Bmatrix} M_0 \\ M_{90} \end{Bmatrix} = \begin{bmatrix} D_{0,flap} & D_{0,edge} \\ D_{90,flap} & D_{90,edge} \end{bmatrix} \begin{Bmatrix} s_{hp} - s_{lp} \\ s_{le} - s_{te} \end{Bmatrix} + \begin{Bmatrix} B_0 \\ B_{90} \end{Bmatrix}$$

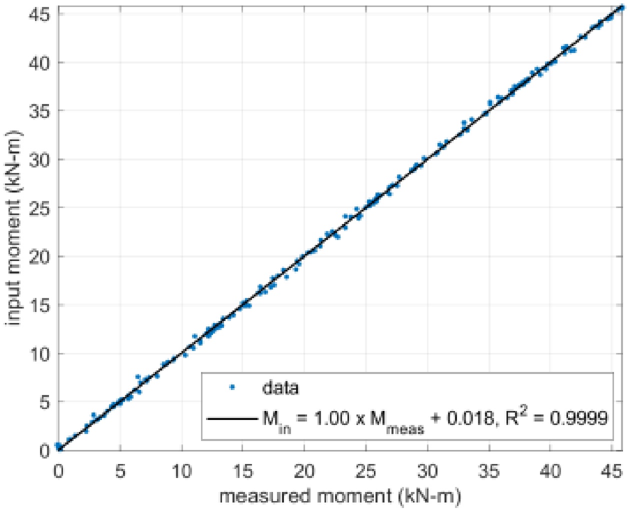
Inverse matrix to calculate coefficients to calculate moment from strain

$$[C] = [A]^{-1}$$

Equation for calculating moment from strain

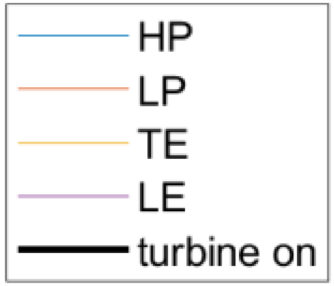
$$\begin{Bmatrix} M_{flap} \\ M_{edge} \end{Bmatrix} = \begin{bmatrix} C_{0,flap} & C_{90,flap} \\ C_{0,edge} & C_{90,edge} \end{bmatrix} \begin{Bmatrix} (s_{hp} - s_{lp}) - B_{flap} \\ (s_{le} - s_{te}) - B_{edge} \end{Bmatrix}$$

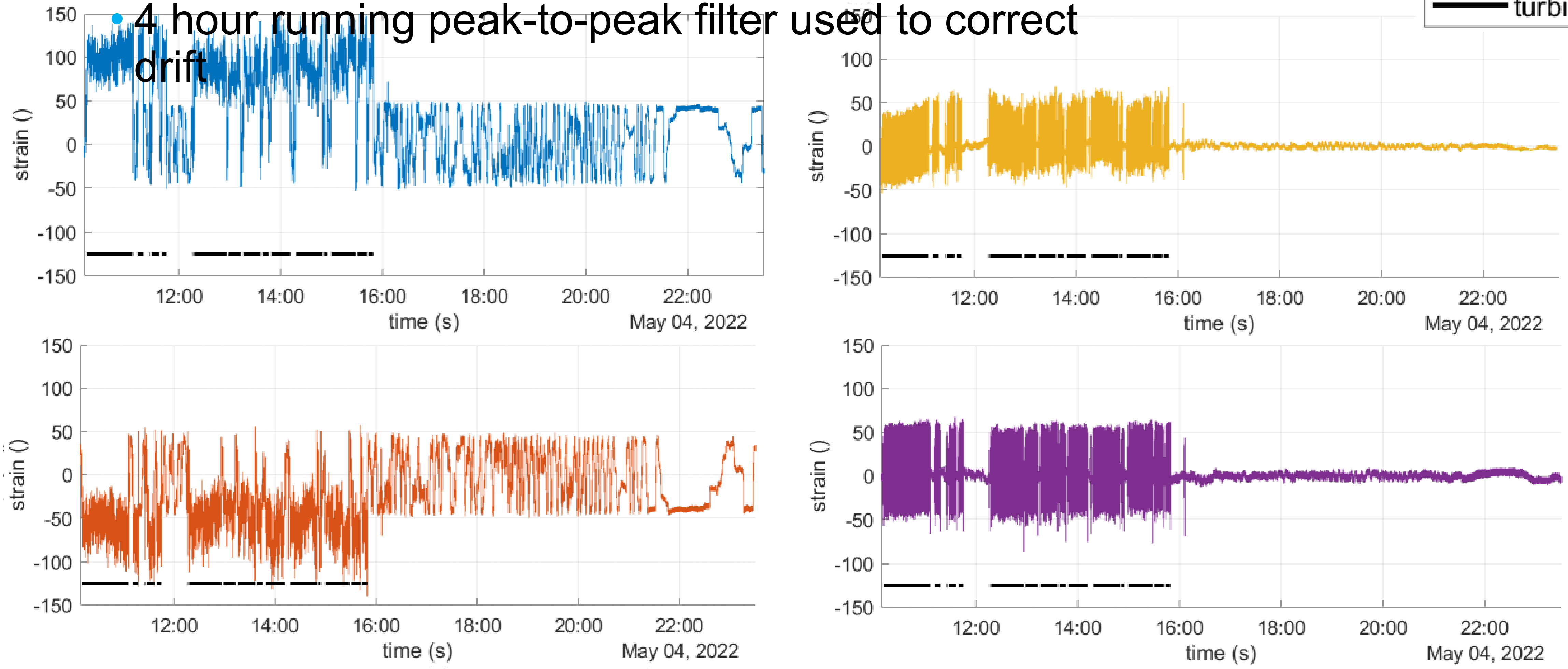




New Field Calibration Process

- Strain drift observed on the scale of the diurnal cycle
- Believed due to creep in the strain gauge adhesive
- 4 hour running peak-to-peak filter used to correct drift

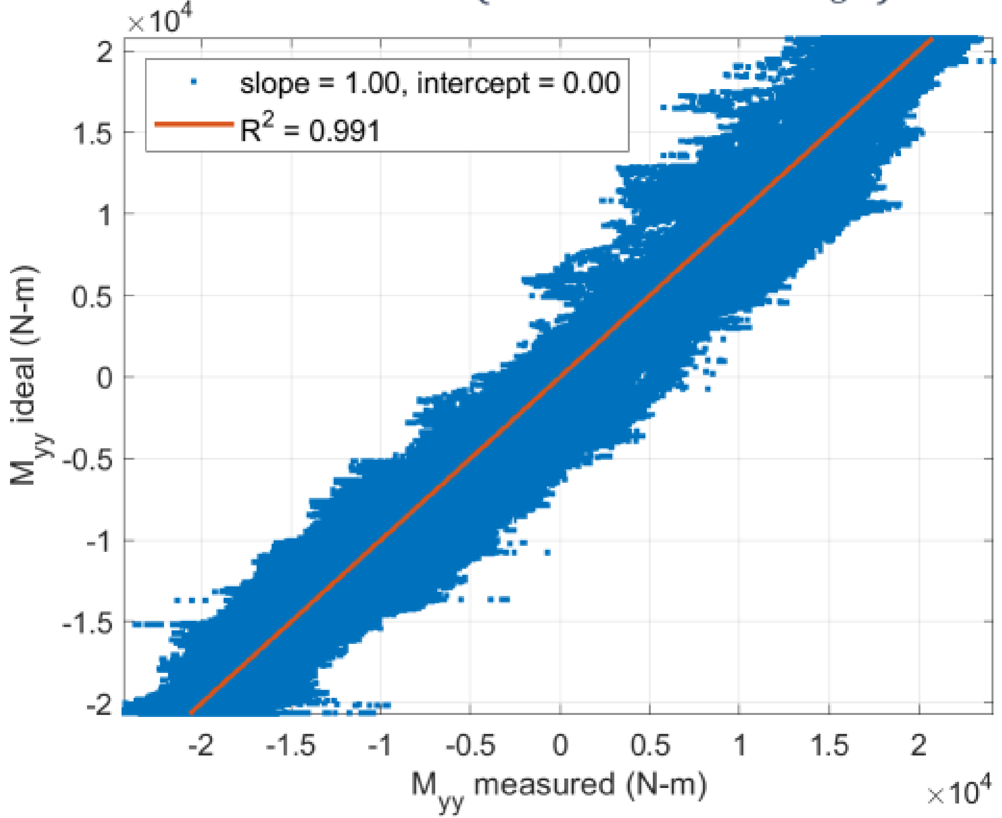




New Field Calibration Process

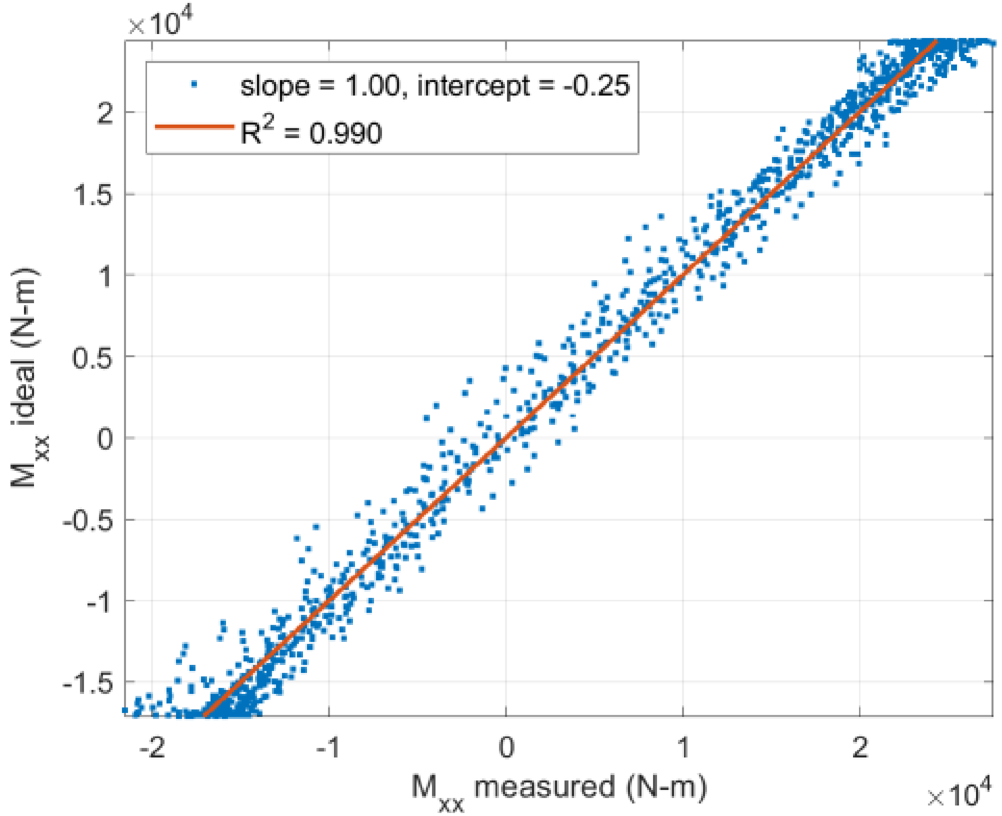
M_0 Pull

$$M_{flap} = C_{0,flap}\{(s_{hp} - s_{lp}) - B_{flap}\} + C_{90,flap}\{(s_{le} - s_{te}) - B_{edge}\}$$

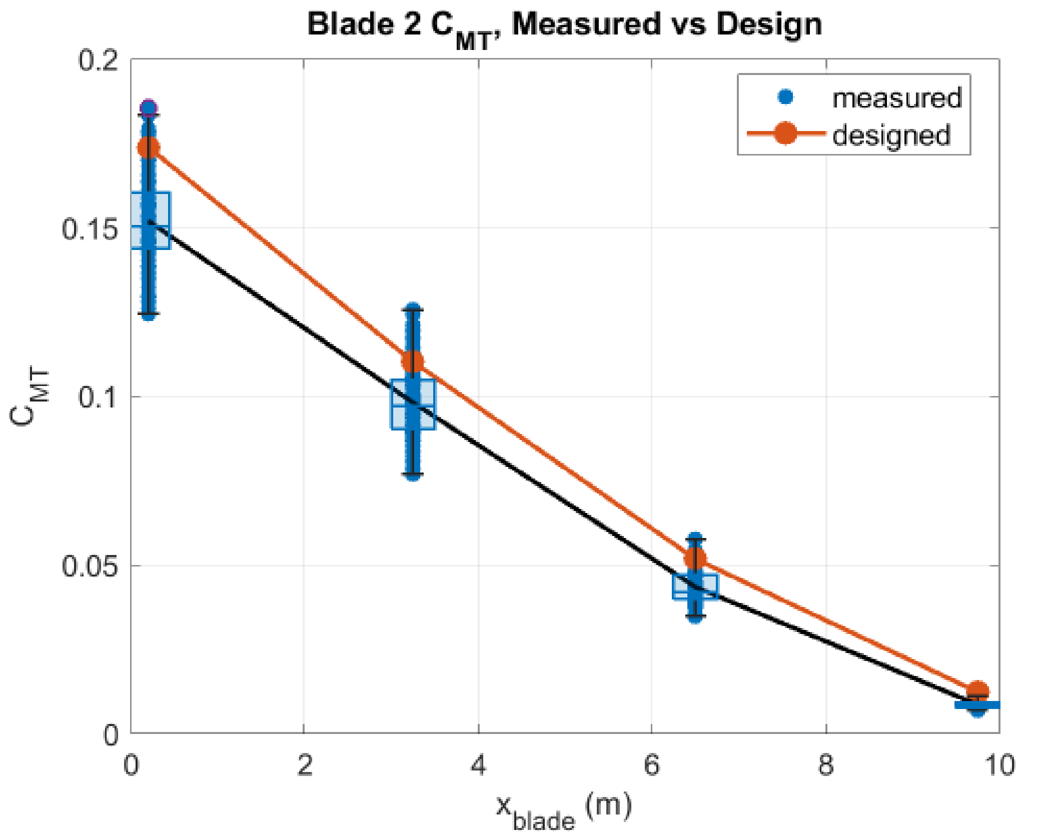


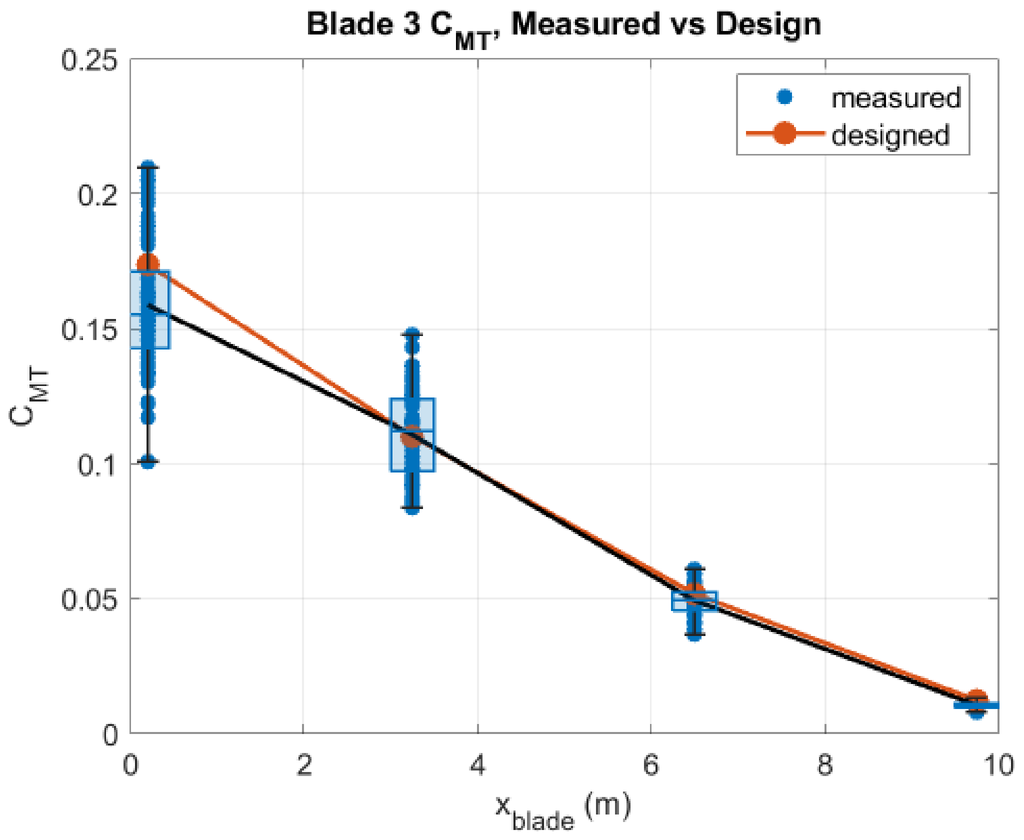
M_{90} Pull

$$M_{edge} = C_{0,edge}\{(s_{hp} - s_{lp}) - B_{flap}\} + C_{90,edge}\{(s_{le} - s_{te}) - B_{edge}\}$$



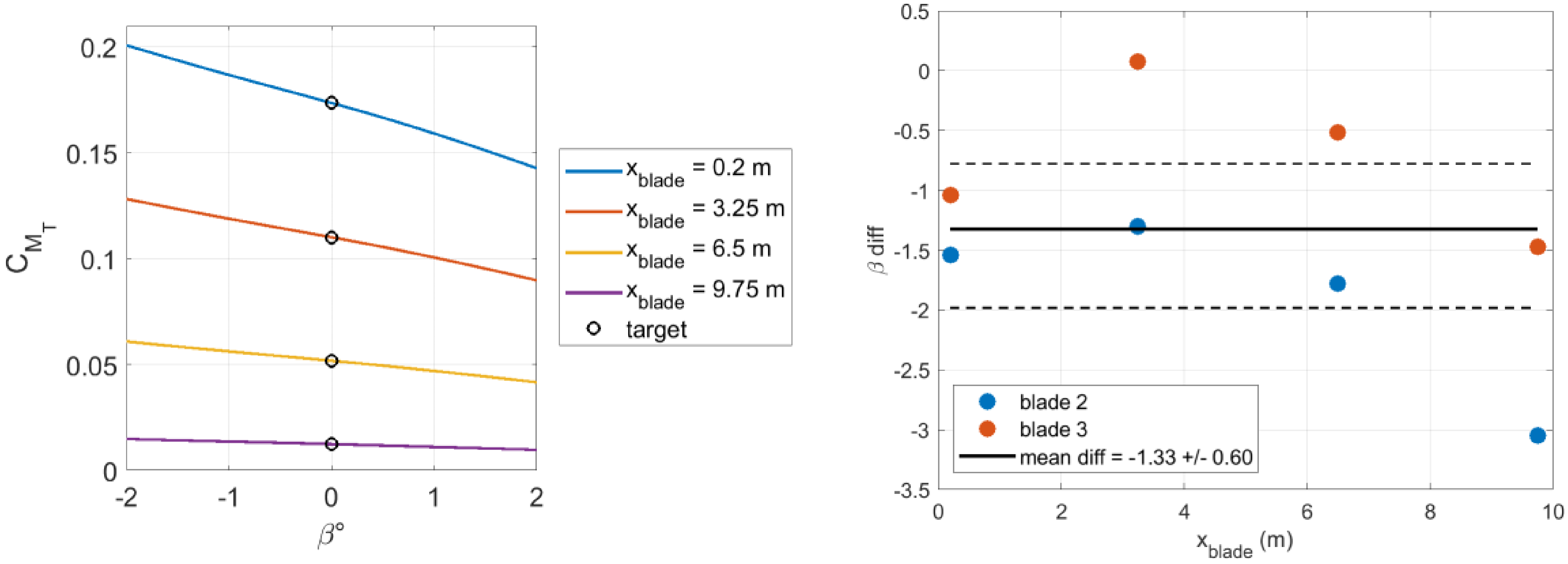
Thrust Bending Moment Coefficient Compared to Design





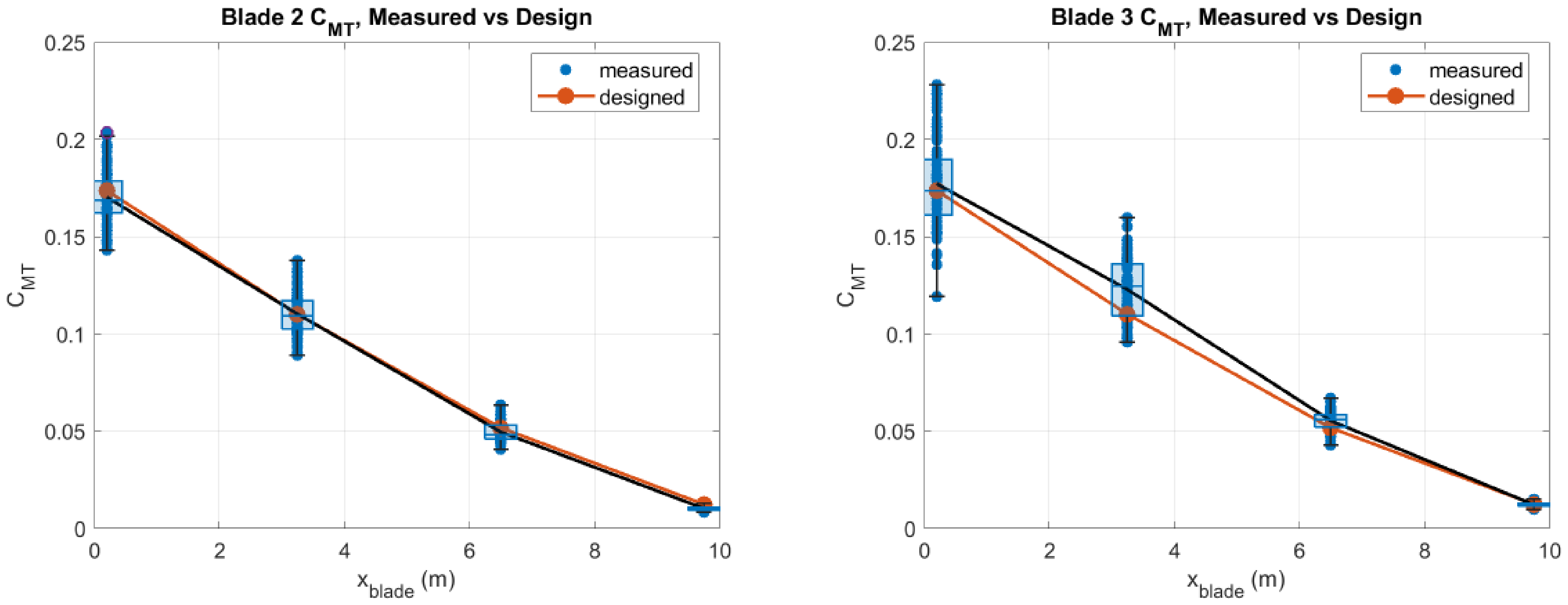
- Relative pitch angle between blades was measured to within 0.1° during installation
- Collective pitch will be adjusted to match design

Pitch Sensitivity and Calibration



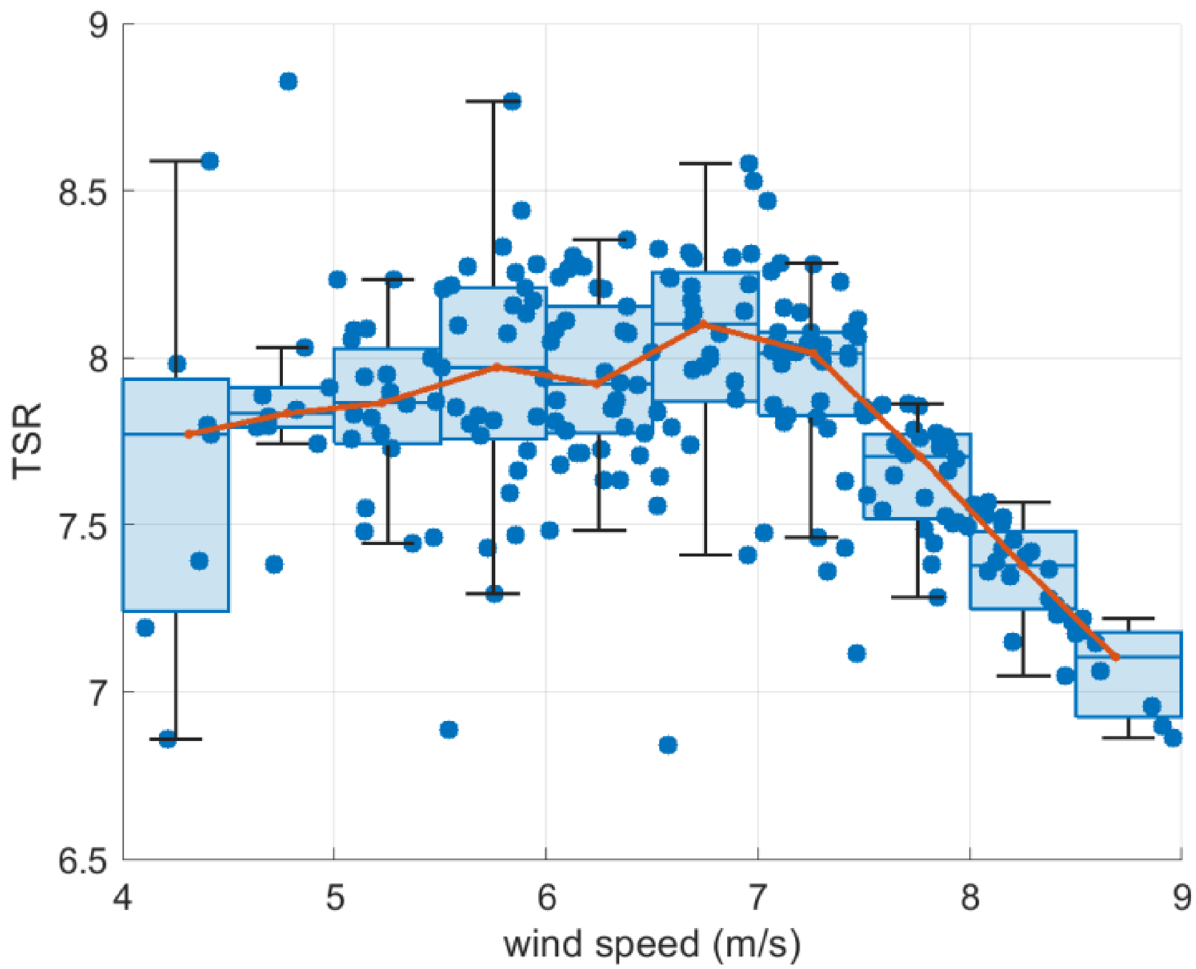
- Used thrust bending moment coefficient versus pitch angle slope to calculate required pitch angle adjustment
- Mean pitch adjustment required is 1.33° towards stall
- Uncertainty bounds estimated using bootstrapping

Anticipated Thrust Bending Moment Coefficient Compared to Design with Pitch Change



- Thrust bending moment coefficient matches well with pitch adjustment
- Largest difference occurs at 0.325 m station on blade 3

Tip-Speed-Ratio Setting



- Tip-Speed-Ratio is low
- Reduce torque constant to increase tip-speed-ratio to 9
- Need to increase tip-speed-ratio by ~11%
- $k \propto \frac{1}{\Omega^3}$
- Reduce torque constant by a factor of ~0.73

Conclusions and Future Work

- FBG strain gauges robust to field testing conditions
  - 12 FBG gauge pairs of 18 survived to date
  - 2 foil gauge pairs of 12 survived to date
- Issues with FBG drift likely due to creep in adhesive
  - Additional testing required to confirm
  - Will provide recommendations
- Developed a field calibration method using feathered rolls, turbine startup, and a running peak-to-peak 4 hour filter
  - Full measurement uncertainty will be estimated
- Collective blade pitch will be adjusted by 1.3° towards stall
- Generator torque constant will be reduced by a factor of ~0.73
- NRT wake will be measured by Spidars and hopefully the SpinnerLidar in the future

Questions?

Back Up

NRT Strain Calibration Equations

Could talk about strain fitting more

$$\begin{Bmatrix} s_{hp} - s_{lp} \\ s_{le} - s_{te} \end{Bmatrix} = \begin{bmatrix} A_{0,flap} & A_{90,flap} \\ A_{0,edge} & A_{90,edge} \end{bmatrix} \begin{Bmatrix} M_0 \\ M_{90} \end{Bmatrix} + \begin{Bmatrix} B_{flap} \\ B_{edge} \end{Bmatrix}$$

$$s_{hp} - s_{lp} = A_{0,flap} M_0 + A_{90,flap} M_{90} + B_{flap}$$
$$s_{le} - s_{te} = A_{0,edge} M_0 + A_{90,edge} M_{90} + B_{edge}$$

$$\begin{Bmatrix} M_0 \\ M_{90} \end{Bmatrix} = \begin{bmatrix} D_{0,flap} & D_{0,edge} \\ D_{90,flap} & D_{90,edge} \end{bmatrix} \begin{Bmatrix} s_{hp} - s_{lp} \\ s_{le} - s_{te} \end{Bmatrix} + \begin{Bmatrix} B_0 \\ B_{90} \end{Bmatrix}$$

$$M_0 = D_{0,flap}(s_{hp} - s_{lp}) + D_{0,edge}(s_{le} - s_{te}) + B_0$$
$$M_{90} = D_{90,flap}(s_{hp} - s_{lp}) + D_{90,edge}(s_{le} - s_{te}) + B_{90}$$

Create a model for M0 and M90 using data from 2 pulls

Use M0 and M90 model to ensure that the cross-talk moment covers the strain range