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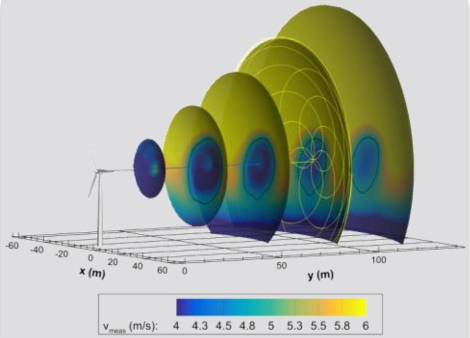

Uncertainty Quantification of Wind Turbine Blade Load Measurement, Estimation, and Transformation

Brandon L. Ennis, Joshua A. Paquette, and Jonathan R. White

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Motivation

OBJECTIVE

Ongoing effort within the U.S. Department of Energy Atmosphere to Electrons (A2e) program to validate computational models

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Experiments will be performed at the DOE/SNL Scaled Wind Farm Technologies (SWiFT) facility and compared to simulations

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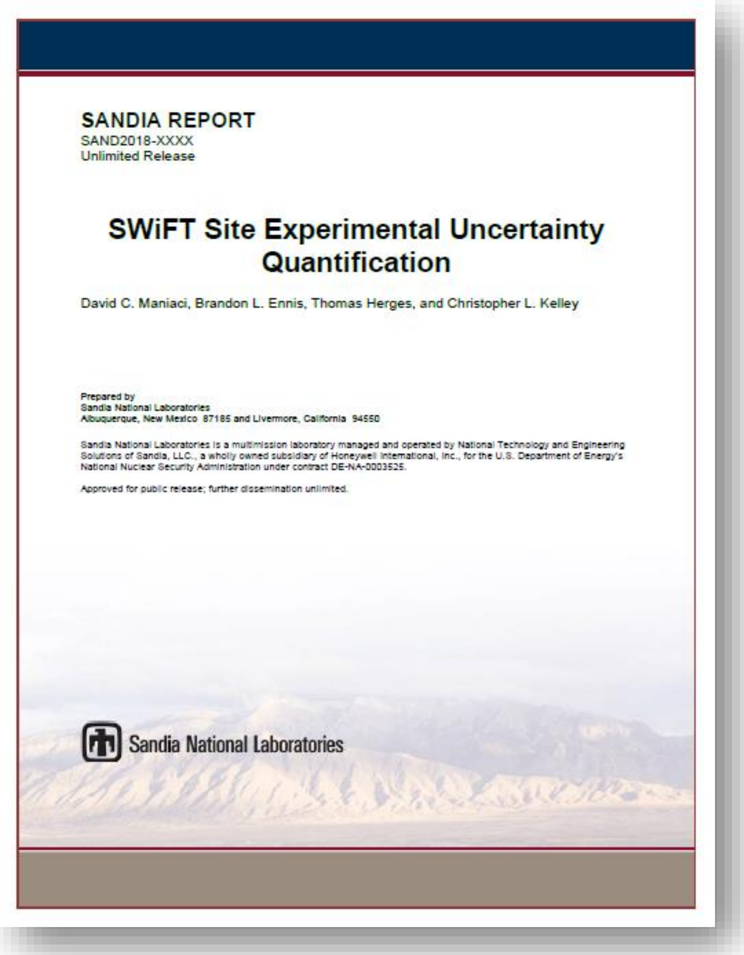
Work at Sandia is being completed this year to quantify uncertainty in the measurements at SWiFT



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SWiFT Site Experimental Uncertainty Quantification

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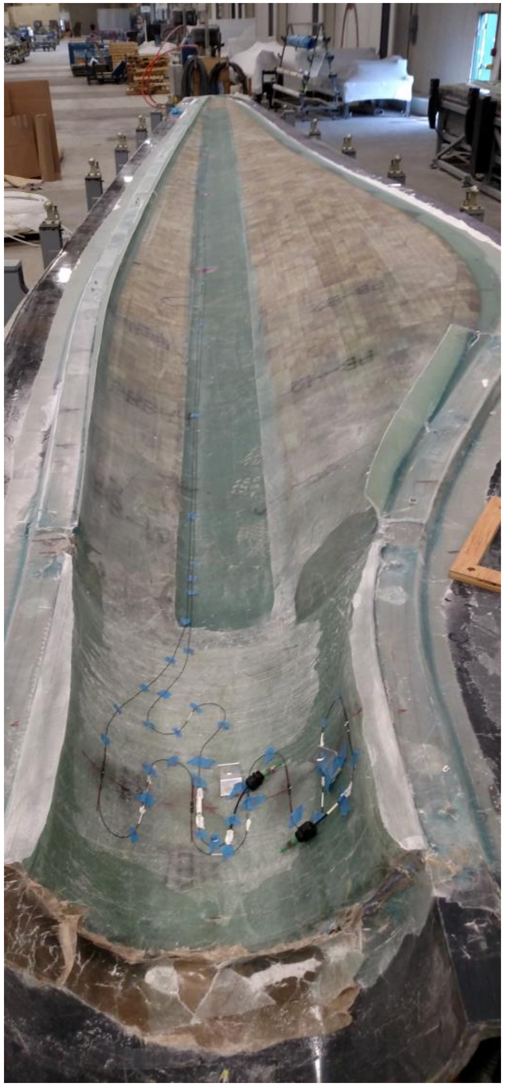
Experimental Setup

- SWiFT facility, 13m long blades
- Fiber optic strain gages in blade root the V27 OEM blades, 2 pairs
- The National Rotor Testbed (NRT) blades have distributed strain measurements at 4 spanwise stations including 4 pairs in the blade root
- Strain gages are mounted purely axially with thermal compensation from fiber optic temperature sensors



Uncertainty Quantification Methods

- Using the classic propagation of uncertainty equation for quantity of interest X, as a function of variables $\{x_i\}$:

$$\delta X = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial X}{\partial x_i} \delta x_i \right)^2}$$

- Assumptions:
  - Variables are uncorrelated with each other
  - Variables have Gaussian distributions for repeated observations
  - The variable uncertainties are at the same level (e.g., 95% confidence)

Blade Load Measurement

Determination of blade loads:

- Measurement is axial blade strain
- Blade moment is calibrated to strain
- Blade transverse shear force can only be inferred
- The load set is then used to determine quantities of interest

Uncertainty in axial strain measurement

- Two fundamental sources of uncertainty in the axially mounted strain gages, due to:
    - The effects of gage misalignment and the presence of shear strain
    - Uncertainty in the strain measurement itself

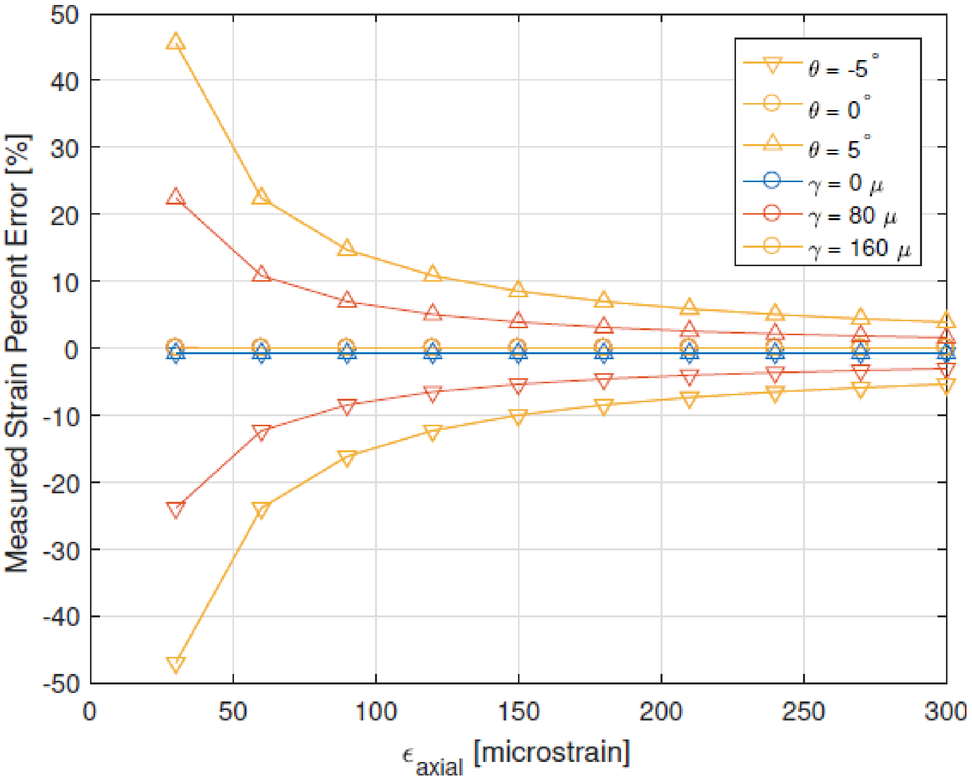
$$\delta\epsilon_s = \sqrt{\delta\epsilon_{s,\gamma}(\theta)^2 + \delta\epsilon_{s,meas}^2}$$

Blade Load Measurement

$$\delta\epsilon_s = \sqrt{\boxed{\delta\epsilon_{s,\gamma}(\theta)^2} + \delta\epsilon^2_{s,meas}}$$

$$\boxed{\epsilon_s = \epsilon\ cos^2\theta - \nu\epsilon\ sin^2\theta + \gamma\ sin\theta cos\theta}$$

- Desired measurement is axial strain
- Error is caused by:
  - gage mounting misalignment (θ)
  - shear strain contribution (ϒ)
- The error in axial strain measurement from these sources is quantified using the strain transformation equation
  - shear strain induced error is negligible when there is no gage misalignment (circle markers)
  - For representative maxima (ϵ_{axial}, ϒ) pairs, the extreme percent error stays within ~5%



Blade Load Measurement

$$\delta\epsilon_s = \sqrt{\delta\epsilon_{s,\gamma}(\theta)^2 + \boxed{\delta\epsilon_{s,meas}^2}}$$

Uncertainty in the strain measurement itself ($\delta\epsilon_{s,meas}$) results from the sensor properties in addition to the compensation and correction procedures

$$\epsilon_{total} = \epsilon_{mech} + \epsilon_{thermal}$$

$$\epsilon_{total} = \epsilon_{aero} + \epsilon_{gravity} + \epsilon_{bias} + \epsilon_{thermal}$$

$$\epsilon_{total} = \frac{\Delta\lambda/\lambda_0}{F_G}$$

$$\epsilon_{s,meas} = \epsilon_{aero} = \frac{\Delta\lambda/\lambda_0}{F_G} - \epsilon_{gravity} - \epsilon_{bias} - CTE * \Delta T$$

$$\delta\epsilon_{s,meas} = \sqrt{\left(\left|\frac{1}{\lambda_0 F_G}\right|\delta\lambda\right)^2 + \delta\epsilon_{gravity}^2 + \delta\epsilon_{bias}^2 + (|\Delta T|\,\delta CTE)^2 + (|CTE|\,\delta T)^2}$$

Blade Load Measurement

- Root bending moment is calibrated for the V27 OEM blades to a strain differential
  - 1 microstrain ~ 700 Nm
- The highest contributor to the uncertainty in axial strain is the uncertainty due to shear and gage misalignment
  - Can be reduced with highly accurate placement of the sensors, or with strain bending bridges (unavailable)
- Combination of strain corrections produces an uncertainty in the strain measurement which is double the sensor accuracy

$$M_{bending} = K_{cal}[kNm/\mu] * \Delta\epsilon_s$$

$$\delta M_{bending} = \sqrt{2\left(|K_{cal}|\,\delta\epsilon_s\right)^2 + 2\left(|\epsilon_s|\,\delta K_{cal}\right)^2}$$

Term $[x]$	Units	Uncertainty $[\delta\overline{x}]$
$\delta\epsilon_{total}$	$[\mu]$	0.823
$\delta\epsilon_{gravity}$	$[\mu]$	-
$\delta\epsilon_{bias}$	$[\mu]$	0.823
$\delta\epsilon_{thermal}$	$[\mu]$	1.147
$\delta\epsilon_{s,meas}$	$[\mu]$	1.635
$\delta\epsilon_{s,\gamma}$	$[\%\epsilon]$	2
$\delta\epsilon_s$	$[\mu]$	$\sqrt{(0.02\ \epsilon)^2 + 2.673}$
$\delta M_{bending}$	$[kNm]$	$\sqrt{0.0002\ M_b^2 + 2.62}$

Blade Load Transformation

- Blade root loads need to be transformed to actual quantities of interest on the wind turbine
    - Requires both coordinate rotations (R_{xyz}) and translations (T_{xyz})

$$\begin{bmatrix} F_{x2} \\ F_{y2} \\ F_{z2} \\ M_{x2} \\ M_{y2} \\ M_{z2} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} F/F \end{bmatrix} & \begin{bmatrix} F/M \end{bmatrix} \\ \begin{bmatrix} M/F \end{bmatrix} & \begin{bmatrix} M/M \end{bmatrix} \end{bmatrix} * \begin{bmatrix} F_{x1} \\ F_{y1} \\ F_{z1} \\ M_{x1} \\ M_{y1} \\ M_{z1} \end{bmatrix}$$

$$\begin{bmatrix} F_{x2} \\ F_{y2} \\ F_{z2} \\ M_{x2} \\ M_{y2} \\ M_{z2} \end{bmatrix} = \begin{bmatrix} cos\theta_y cos\theta_z & sin\theta_z & -sin\theta_y & 0 & 0 & 0 \\ -sin\theta_z & cos\theta_x cos\theta_z & sin\theta_x & 0 & 0 & 0 \\ sin\theta_y & -sin\theta_x & cos\theta_x cos\theta_y & 0 & 0 & 0 \\ 0 & d_z & -d_y & cos\theta_y cos\theta_z & sin\theta_z & -sin\theta_y \\ -d_z & 0 & d_x & -sin\theta_z & cos\theta_x cos\theta_z & sin\theta_x \\ d_y & -d_x & 0 & sin\theta_y & -sin\theta_x & cos\theta_x cos\theta_y \end{bmatrix} \begin{bmatrix} F_{x1} \\ F_{y1} \\ F_{z1} \\ M_{x1} \\ M_{y1} \\ M_{z1} \end{bmatrix}$$

Blade Load Transformation

- Transformation to blade loads to rotor torque
  - Rotation from the root strain gage pair to the rotational plane
  - Translation from the root location to the rotor shaft centerline

$$R_z(\theta_{rotorplane}) \rightarrow R_z(\beta_0) \rightarrow R_y(\theta_{precone}) \rightarrow T_z(d_{gage})$$

- Depends on the transverse shear forces because you are not measuring the moment directly at the rotor axis

$$\begin{aligned}\tau_{aero,B} = & \, d_{gage} * sin\beta_0 * (F_{x'} cos\theta_{rotorplane} + F_{y'} sin\theta_{rotorplane}) \\ & - d_{gage} * cos\beta_0 * (-F_{x'} sin\theta_{rotorplane} + F_{y'} cos\theta_{rotorplane}) \\ & + cos\beta_0 * (M_{x'} cos\theta_{rotorplane} + M_{y'} sin\theta_{rotorplane}) \\ & + sin\beta_0 * (-M_{x'} sin\theta_{rotorplane} + M_{y'} cos\theta_{rotorplane})\end{aligned}$$

$$\tau_{aero,rotor} = \tau_{aero,B1} + \tau_{aero,B2} + \tau_{aero,B3}$$

Blade Load Transformation

- Transformation to blade loads to rotor thrust
  - Requires additional rotation transformations to account for the shaft tilt angle

$$R_z(\theta_{rotorplane}) \rightarrow R_z(\beta_0) \rightarrow R_y(\theta_{precone}) \rightarrow T_z(d_{gage}) \rightarrow R_x(-\psi) \rightarrow R_y(-\theta_{shafttilt})$$

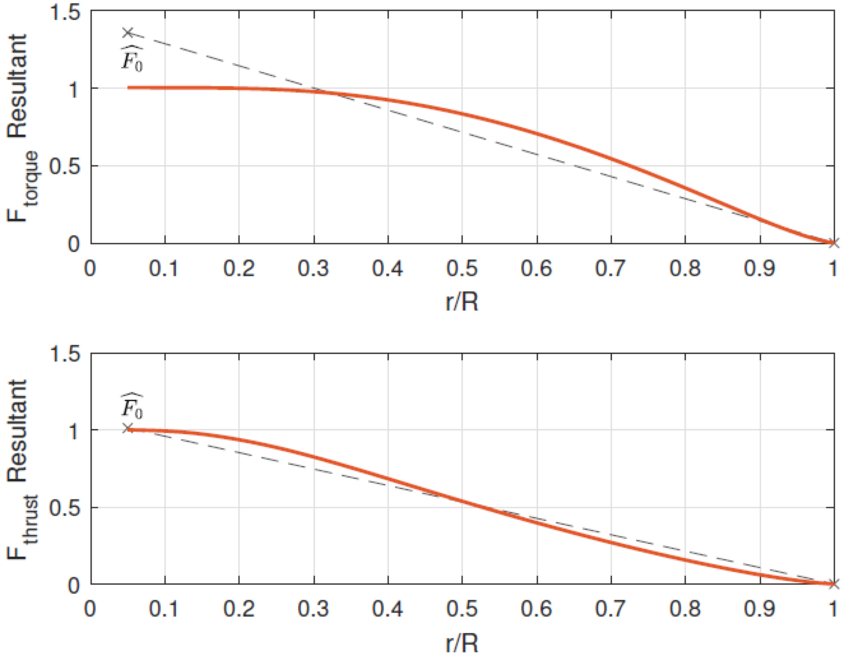
- Depends only on the transverse shear forces, which you are not actually measuring

$$\begin{aligned}
T_B = {} & cos\theta_{shafttilt} * cos\beta_0 * (F_{x'} cos\theta_{rotorplane} + F_{y'} sin\theta_{rotorplane}) \\
& + cos\theta_{shafttilt} * sin\beta_0 * (-F_{x'} sin\theta_{rotorplane} + F_{y'} cos\theta_{rotorplane}) \\
& - sin\theta_{shafttilt} * sin\psi * sin\beta_0 * (F_{x'} cos\theta_{rotorplane} + F_{y'} sin\theta_{rotorplane}) \\
& + sin\theta_{shafttilt} * sin\psi * cos\beta_0 * (-F_{x'} sin\theta_{rotorplane} + F_{y'} cos\theta_{rotorplane}) \\
& + sin\theta_{shafttilt} * cos\psi * F_{z'}
\end{aligned}$$

$$T_{rotor} = T_{B1} + T_{B2} + T_{B3}$$

Blade Force Estimation

- Root bending moment is the result of spanwise forces
- Spanwise forces can be inferred generically for a wind turbine using blade element momentum
- As an approximation, the spanwise resultant force profile is estimated using a linear profile to then relate moment to resultant force

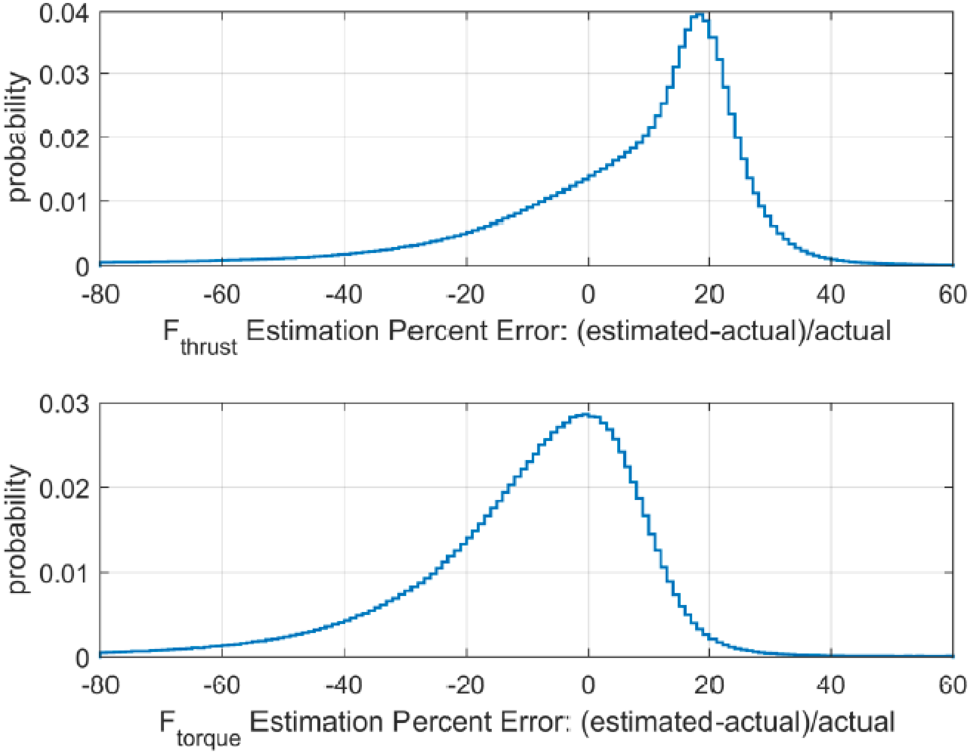


$$\frac{dF_{\tau}}{dr} = \frac{1}{2}\rho U^2 C_l * c * \left((1-a)^2 + TSR^2\left(\frac{r}{R}\right)^2(1+a')^2\right)\left(cos(90^\circ-\phi) - \frac{C_d}{C_l}cos(\phi)\right)$$

$$\frac{dF_T}{dr} = \frac{1}{2}\rho U^2 C_l * c * \left((1-a)^2 + TSR^2\left(\frac{r}{R}\right)^2(1+a')^2\right)\left(sin(90^\circ-\phi) + \frac{C_d}{C_l}sin(\phi)\right)$$

Blade Force Estimation

- The generic approximation produces high percent errors in the inferred shear forces at the blade root, when comparing aeroelastic simulations using the NREL FAST code



$$\delta\widehat{F}_{x',95\%} = \begin{cases} -52.0\% \\ +31.6\% \end{cases}$$

$$\delta\widehat{F}_{y',95\%} = \begin{cases} -61.2\% \\ +15.5\% \end{cases}$$

Initial Results and Discussion

- The uncertainty in torque estimated using blade root loads results from 7 variables and their uncertainties

$$\delta\tau^2_{aero,B} = \left(\left|\frac{\partial\tau_B}{\partial M_{x'}}\right|\delta M_{x'}\right)^2 + \left(\left|\frac{\partial\tau_B}{\partial M_{y'}}\right|\delta M_{y'}\right)^2 + \left(\left|\frac{\partial\tau_B}{\partial F_{x'}}\right|\delta F_{x'}\right)^2 + \left(\left|\frac{\partial\tau_B}{\partial F_{y'}}\right|\delta F_{y'}\right)^2 + \left(\left|\frac{\partial\tau_B}{\partial d_{gage}}\right|\delta d_{gage}\right)^2 + \left(\left|\frac{\partial\tau_B}{\partial\beta_0}\right|\delta\beta_0\right)^2 + \left(\left|\frac{\partial\tau_B}{\partial\theta_{rotorplane}}\right|\delta\theta_{rotorplane}\right)^2$$

- The uncertainty in thrust estimated using blade root loads results from 7 variables and their uncertainties

$$\delta T_B^2 = \left(\left|\frac{\partial T_B}{\partial F_{x'}}\right|\delta F_{x'}\right)^2 + \left(\left|\frac{\partial T_B}{\partial F_{y'}}\right|\delta F_{y'}\right)^2 + \left(\left|\frac{\partial T_B}{\partial F_{z'}}\right|\delta F_{z'}\right)^2 + \left(\left|\frac{\partial T_B}{\partial\theta_{shafttilt}}\right|\delta\theta_{shafttilt}\right)^2 + \left(\left|\frac{\partial T_B}{\partial\theta_{rotorplane}}\right|\delta\theta_{rotorplane}\right)^2 + \left(\left|\frac{\partial T_B}{\partial\beta_0}\right|\delta\beta_0\right)^2 + \left(\left|\frac{\partial T_B}{\partial\psi}\right|\delta\psi\right)^2$$

Initial Results and Discussion

- Initial results are derived to identify the largest contributors to uncertainty in the quantities of interest, and should not be taken as final values at this current stage

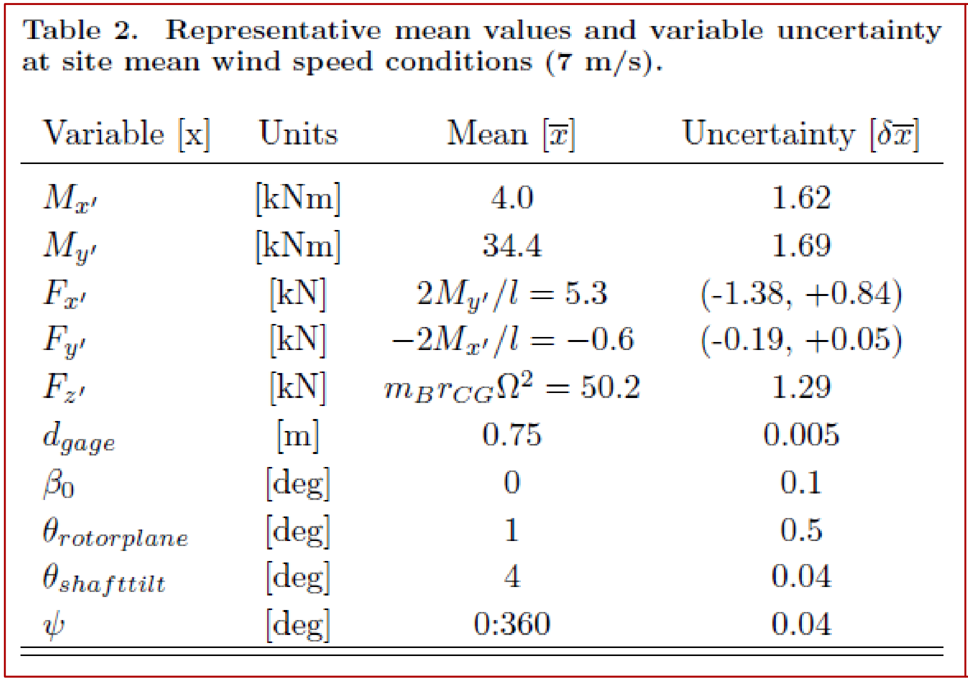


Table 2. Representative mean values and variable uncertainty at site mean wind speed conditions (7 m/s).

Variable [x]	Units	Mean [$\overline{x}$]	Uncertainty [$\delta\overline{x}$]
$M_{x'}$	[kNm]	4.0	1.62
$M_{y'}$	[kNm]	34.4	1.69
$F_{x'}$	[kN]	$2M_{y'}/l = 5.3$	(-1.38, +0.84)
$F_{y'}$	[kN]	$-2M_{x'}/l = -0.6$	(-0.19, +0.05)
$F_{z'}$	[kN]	$m_B r_{CG} \Omega^2 = 50.2$	1.29
d_{gage}	[m]	0.75	0.005
β_0	[deg]	0	0.1
$\theta_{rotorplane}$	[deg]	1	0.5
$\theta_{shafttilt}$	[deg]	4	0.04
ψ	[deg]	0:360	0.04

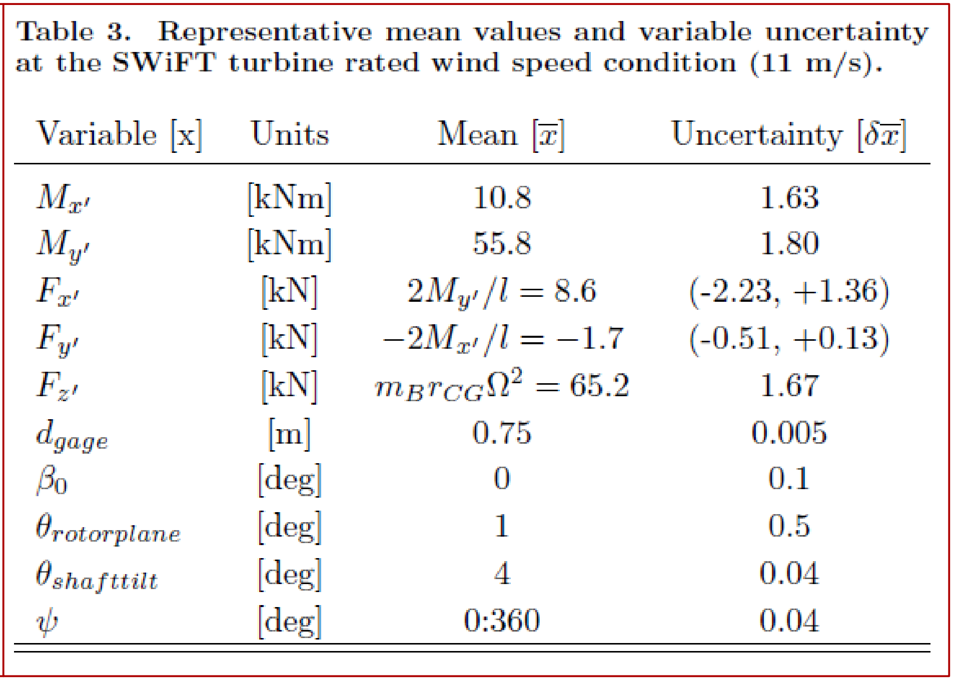
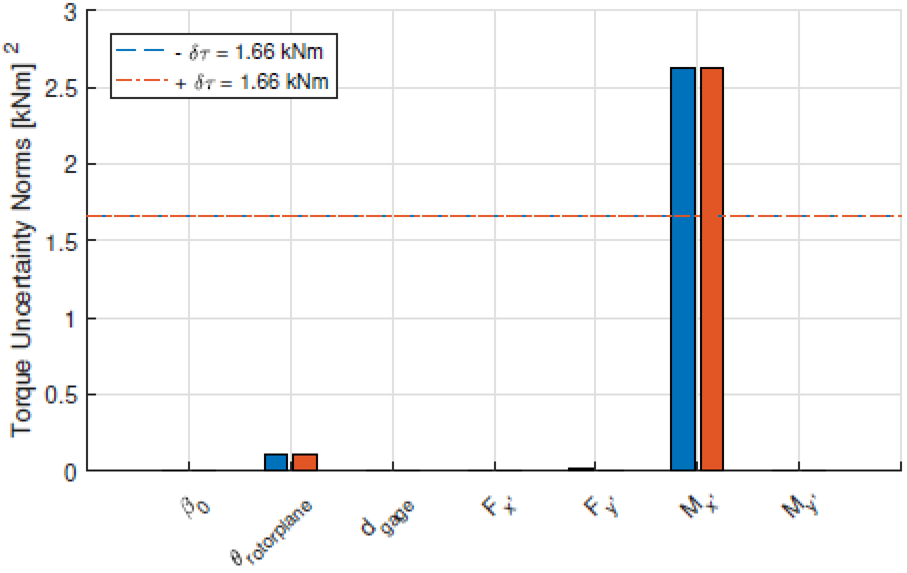


Table 3. Representative mean values and variable uncertainty at the SWiFT turbine rated wind speed condition (11 m/s).

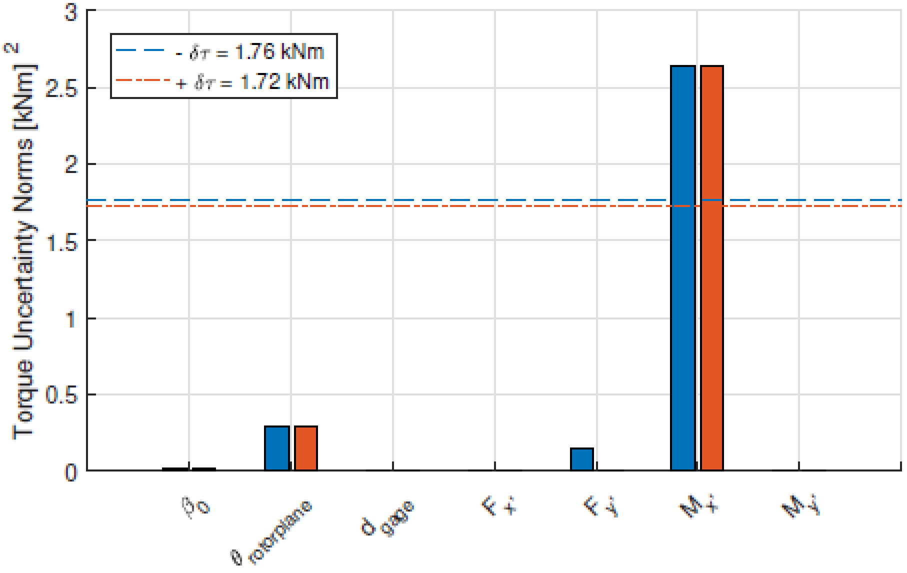
Variable [x]	Units	Mean [$\overline{x}$]	Uncertainty [$\delta\overline{x}$]
$M_{x'}$	[kNm]	10.8	1.63
$M_{y'}$	[kNm]	55.8	1.80
$F_{x'}$	[kN]	$2M_{y'}/l = 8.6$	(-2.23, +1.36)
$F_{y'}$	[kN]	$-2M_{x'}/l = -1.7$	(-0.51, +0.13)
$F_{z'}$	[kN]	$m_B r_{CG} \Omega^2 = 65.2$	1.67
d_{gage}	[m]	0.75	0.005
β_0	[deg]	0	0.1
$\theta_{rotorplane}$	[deg]	1	0.5
$\theta_{shafttilt}$	[deg]	4	0.04
ψ	[deg]	0:360	0.04

Initial Results and Discussion

- Uncertainty in torque is mostly produced by the uncertainty in the edgewise bending moment
- The large uncertainty in the shear forces inferred from the bending moment does not contribute significantly due to the small displacement from the rotor axis



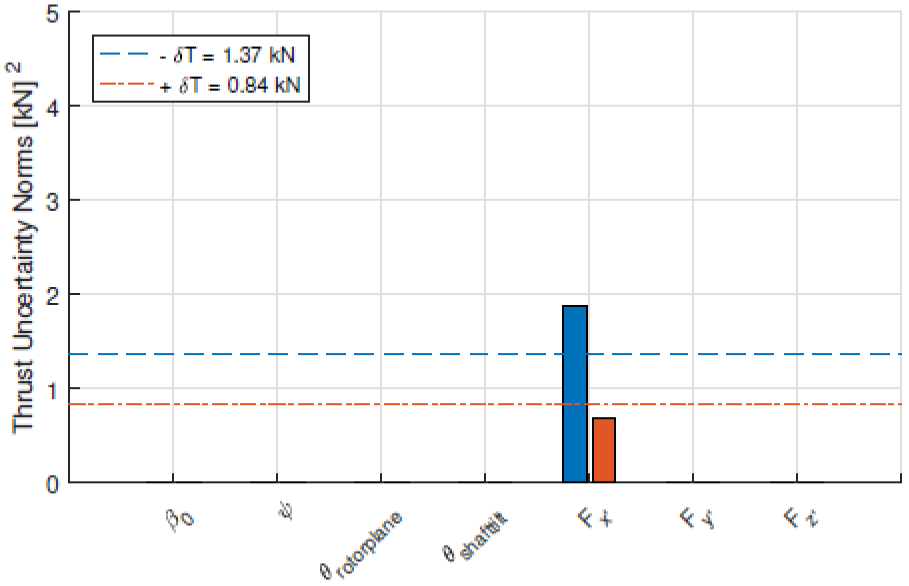
(a) 7 m/s wind speed case (Table 2)



(b) 11 m/s wind speed case (Table 3)

Initial Results and Discussion

- Uncertainty in thrust is almost entirely produced by the uncertainty in the flapwise shear force (0 blade pitch cases)
- The thrust uncertainty is lower than expected considering that blade force is not directly measured, but inferred



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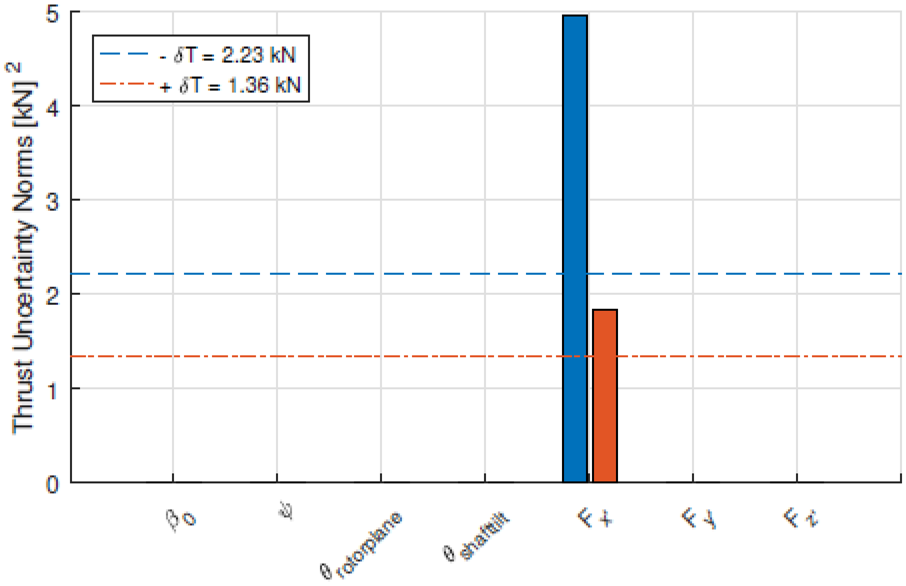

(b) 11 m/s wind speed case (Table 3)

Future Work

- More work is required to approximate the final values of uncertainty for the SWiFT turbines

- A Sandia report will be released this year which will establish uncertainty values for the SWiFT measurements, including the defined methods for inflow, turbine, and wake measurement uncertainty

- The measurement uncertainty will be utilized through targeted experimental campaigns at SWiFT to validate computational models

Thank you for your attention

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