SAND2022-13313C

Rotor Aerodynamics Aeroelastic & Wake Project

RAAW

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Mid-Fidelity Turbulent Inflow Data Assimilation with a 2.8 MW Wind Turbine to Validate Aeroservoelastic Modeling Techniques

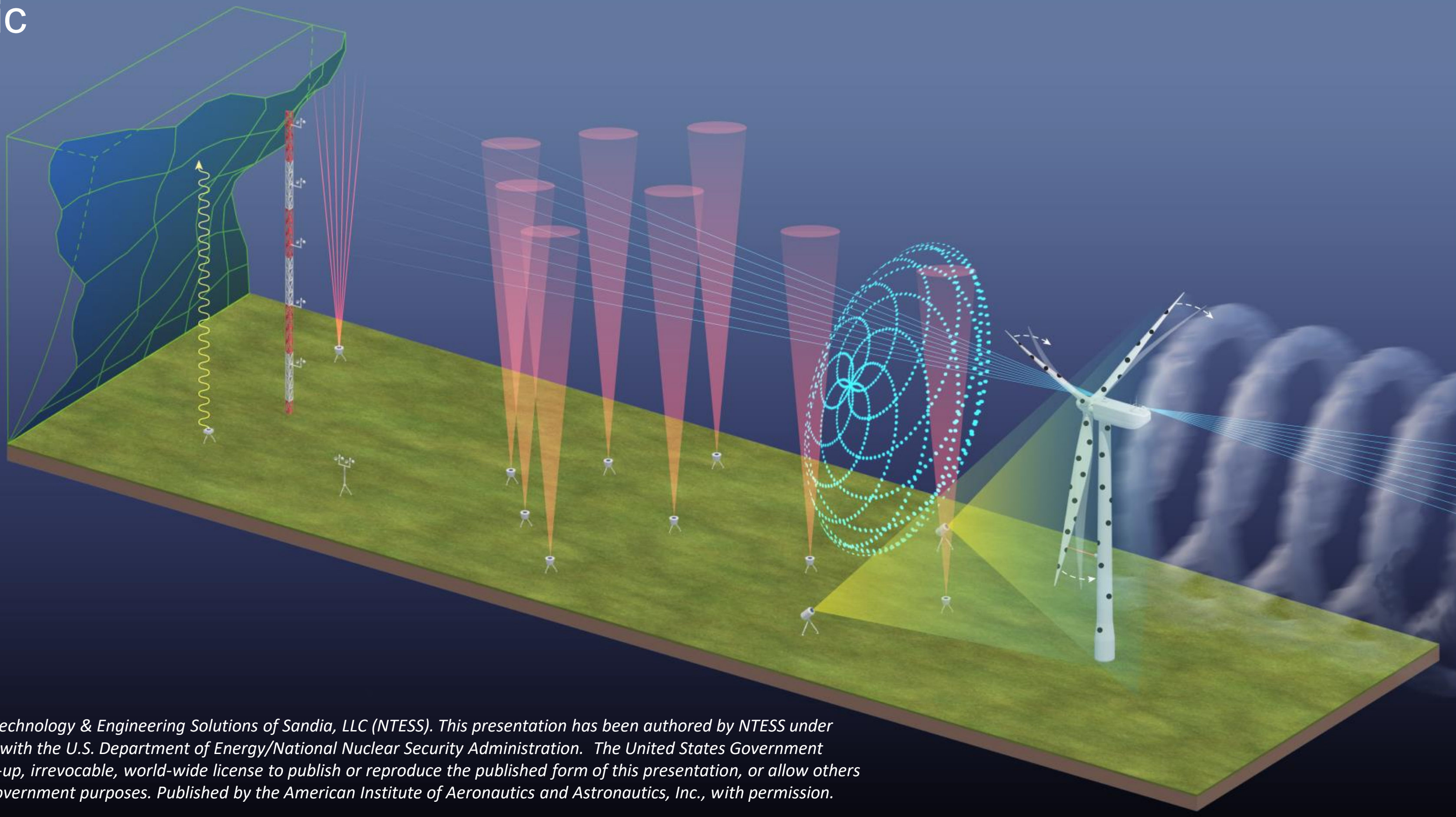

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Photo: Andy Scholbrock/Nicholas Hamilton

Outline

- Inflow
  - Intro to P3 Met Tower
    - Anemometer Instrumentation
    - Selecting 10-Minute Bins
  - Modeling Approaches
- Turbine/Controller
  - Intro to P3 Turbine
  - Modeling Approaches
- Results
- Summary/Plan Forward

Intro to P3 Met Tower: Anemometer Instrumentation

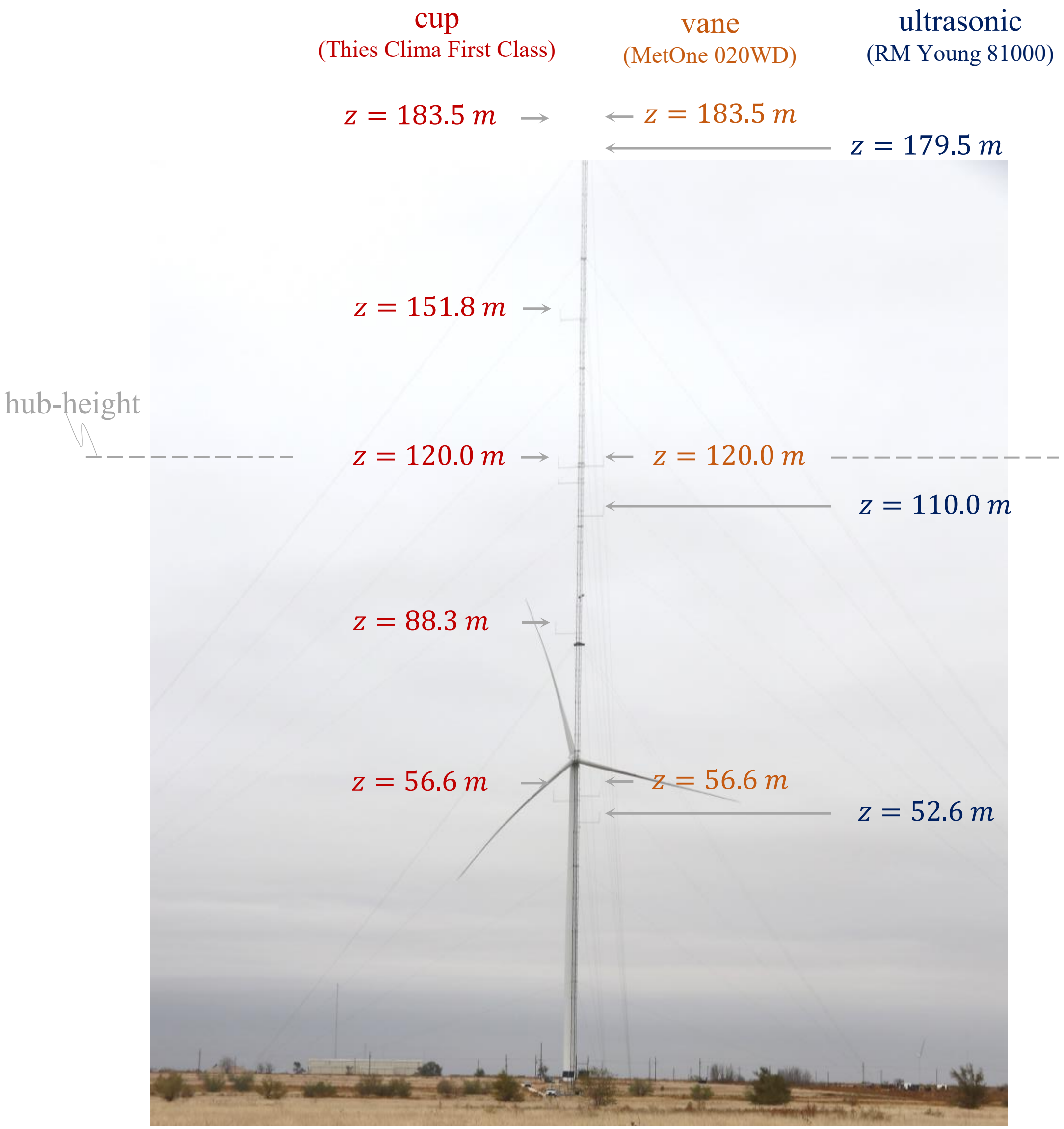


Photo: Andy Scholbrock/Nicholas Hamilton

The P3 met tower to be used in the RAAW experiment has been instrumented with several types of anemometers.

For this study, we utilize ultrasonic anemometers at three heights that approximately span the rotor height.

The ultrasonics are preferred because…

- They provide the w-component of velocity
- They are more reliable than one of the wind vanes

Wind direction data from the ultrasonics was validated against data from a WindCube sitting at the base of the met tower.

Intro to P3 Met Tower: Selecting 10-Minute Bins

Filters applied to measured 10-minute bins*:

	Quantity of interest	Filter type (values)
Wind data	Wind components/speeds/directions	Stuck value over whole bin
Wind data	Wind speed (hub-height only)	Range (3 m/s < mean < 25 m/s)
Wind data	Wind direction (hub-height only)	Range (170° < mean < 200°)
Wind data	Wind shear	Range (-1 < mean < 1)
Wind data	Wind veer	Range (-50° < mean < 50°)
Wind data / Turbine data	Yaw misalignment	Range (|mean| < 10°)
Turbine data	Power	Stuck value over whole bin
Turbine data	Power	Range (0.1 kW < mean < 3000 kW)
Turbine data	Rotor speed	Range (min > 6 rpm)
Turbine data	Blade pitches	Range (max < 20°)

limit wind direction sector to ±15° from the direction of the met tower

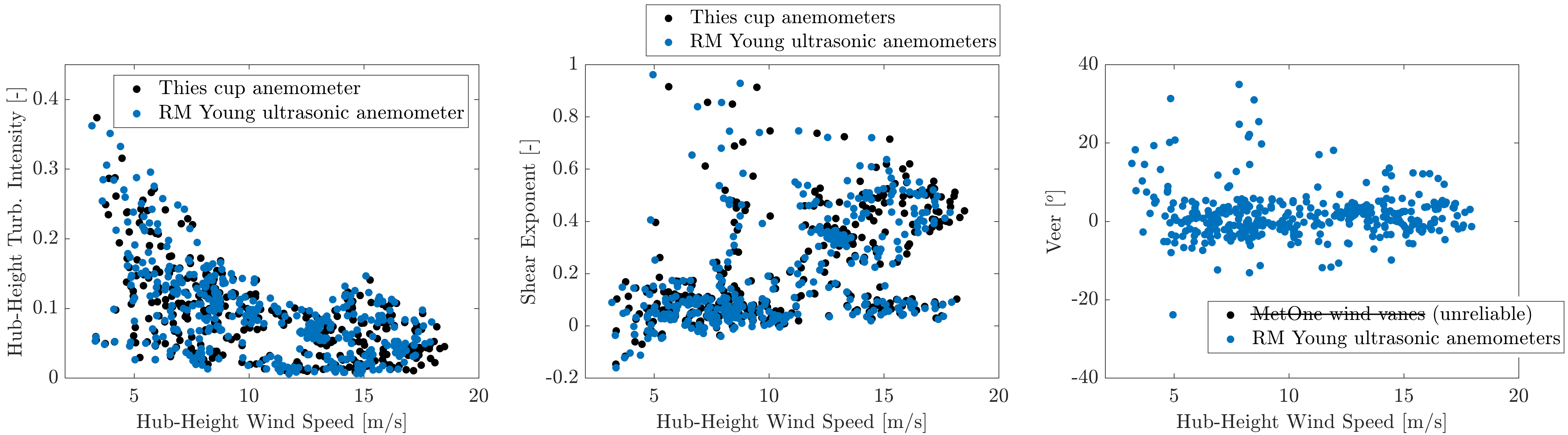
limit cases to non-startup and non-shutdown according to pitch and rotor speed

*only bins with full data availability on all channels (i.e., time series length == 10 min) are considered

Filters are applied to 70 days of measurement data in 2021/22 to produce 2.7 days (382 ten-minute bins) for validation analysis

Intro to P3 Met Tower: Selecting 10-Minute Bins

Distributions of inflow conditions in selected bins:



Diversity of inflow conditions implies a relatively broad range of turbine operating conditions

Modeling Approaches

Three levels of fidelity for inflow data assimilation:

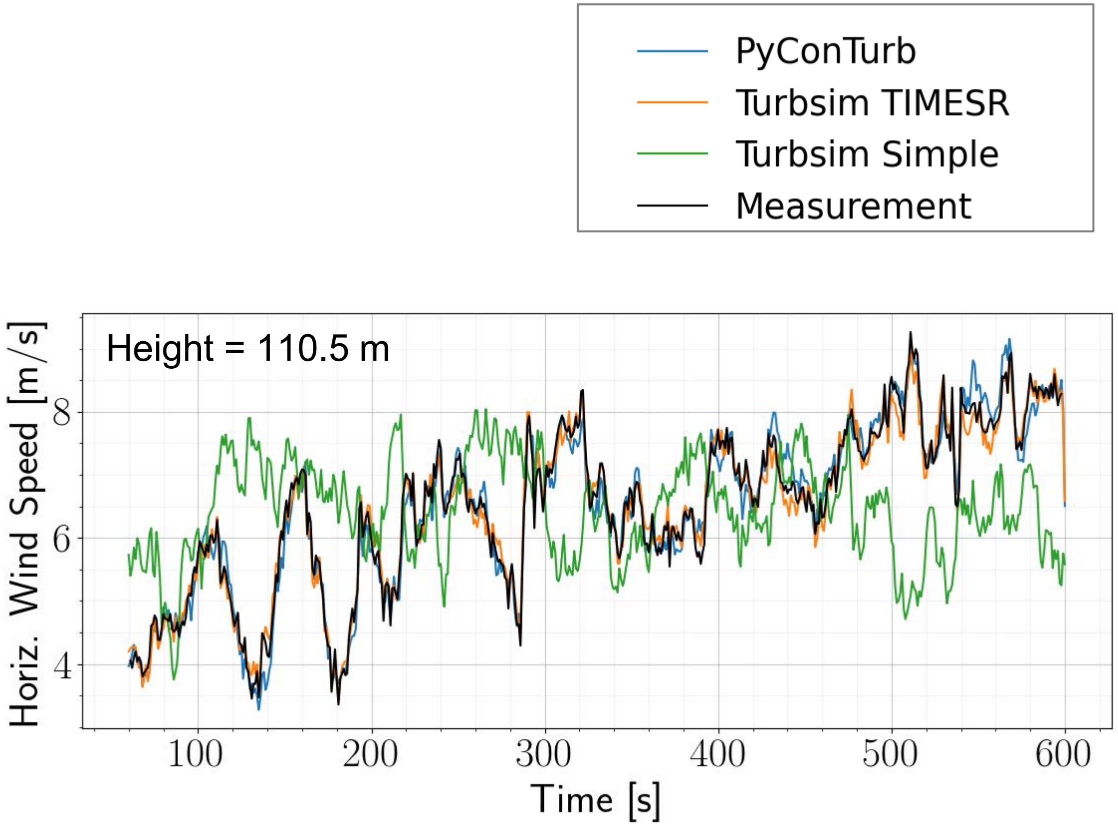
	TurbSim Simple	TurbSim TIMESR	PyConTurb
Turbulence method	Unconstrained Kaimal (TurbModel=IECKAI)	Constrained Kaimal at 1 point with exponential coherence (TurbModel=TIMESR)	Constrained Kaimal at 3 points with exponential coherence
Turbulence magnitudes	Uniform (derived from near-hub-height measurement*)	Linear interpolation from 3-point input	Linear interpolation from 3-point input
Spatial coherence	IEC in u-component, none currently enforced in v and w	GENERAL† in u, v, and w-components	IEC in u-component, none currently enforced in v and w
Wind speed profile	Power law interpolation from 3-point input	Linear interpolation from 3-point input	Linear interpolation from 3-point input
Wind direction profile	None enforced	Linear interpolation from 3-point input	Linear interpolation from 3-point input

*The hub-height velocity time series is linearly detrended before calculating turbulence intensity as per [1], and ScaleIEC is set to 1 to enforce the exact value specified at hub-height given the desired sample rate
†See [2] for description of the coherence model

[1] Larsen, Gunner Chr, and Kurt S. Hansen. "De-trending of wind speed variance based on first-order and second-order statistical moments only." Wind Energy 17.12 (2014): 1905-1924.
[2] Jonkman, B. J. "TurbSim user’s guide v2. 00.00." Natl. Renew. Energy Lab (2014).

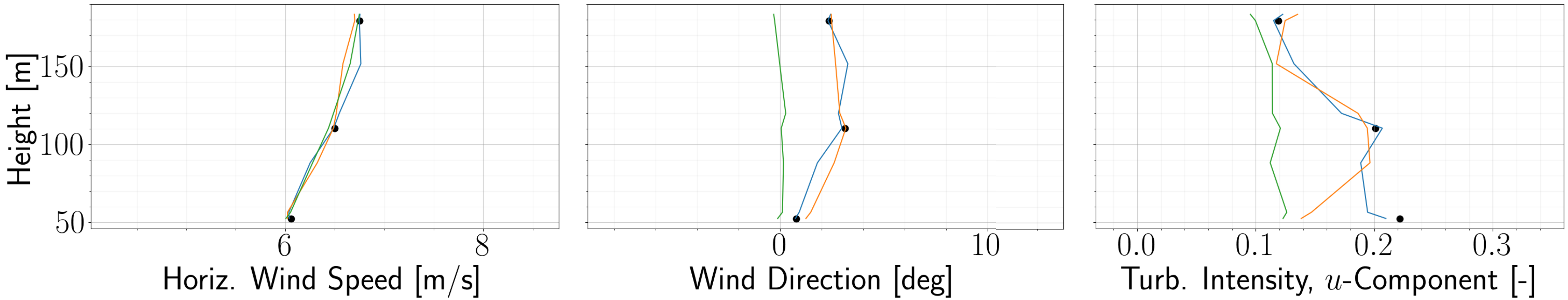
Modeling Approaches

Three levels of fidelity for inflow data assimilation:



Verification of OpenFAST inflow with an example bin and seed:

- TurbSim Simple generally matches only the 10-minute wind profile and turbulence intensity while the constrained methods match one or more measured time series
- Small differences in time series of constrained codes due to non-alignment of the grid with the measurement location
- PyConTurb matches the time series at two other heights (not shown), as well
- Detrending applied to TurbSim Simple inputs results in significantly lower turbulence levels because of the gradient in wind speed during this bin



Modeling Approaches

Inflow generation parameters:

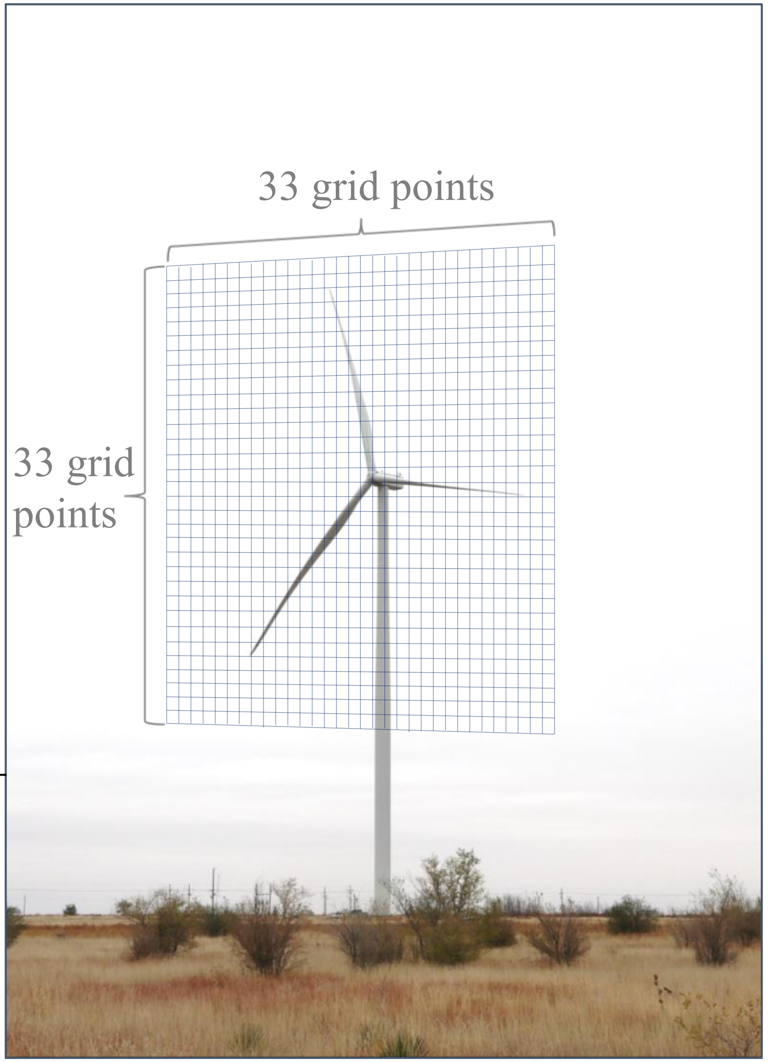
Number of turbulence seeds: 6

Sampling frequency: 1 Hz
- Corresponds to ~4P at rated rotor speed
- Implies error of <2% of flapwise bending damage equivalent load [3]

Grid size: 10% larger than rotor diameter
- 33 by 33 nodes => grid spacing of 4.375 m

Tower nodes: not included

Rotor yaw is enforced to the mean measured value
(as compared to the hub-height wind vane)



[3] Sim, Chungwook, Sukanta Basu, and Lance Manuel. "On space-time resolution of inflow representations for wind turbine loads analysis." *Energies* 5.7 (2012): 2071-2092.

Photo: Andy Scholbrock/Nicholas Hamilton

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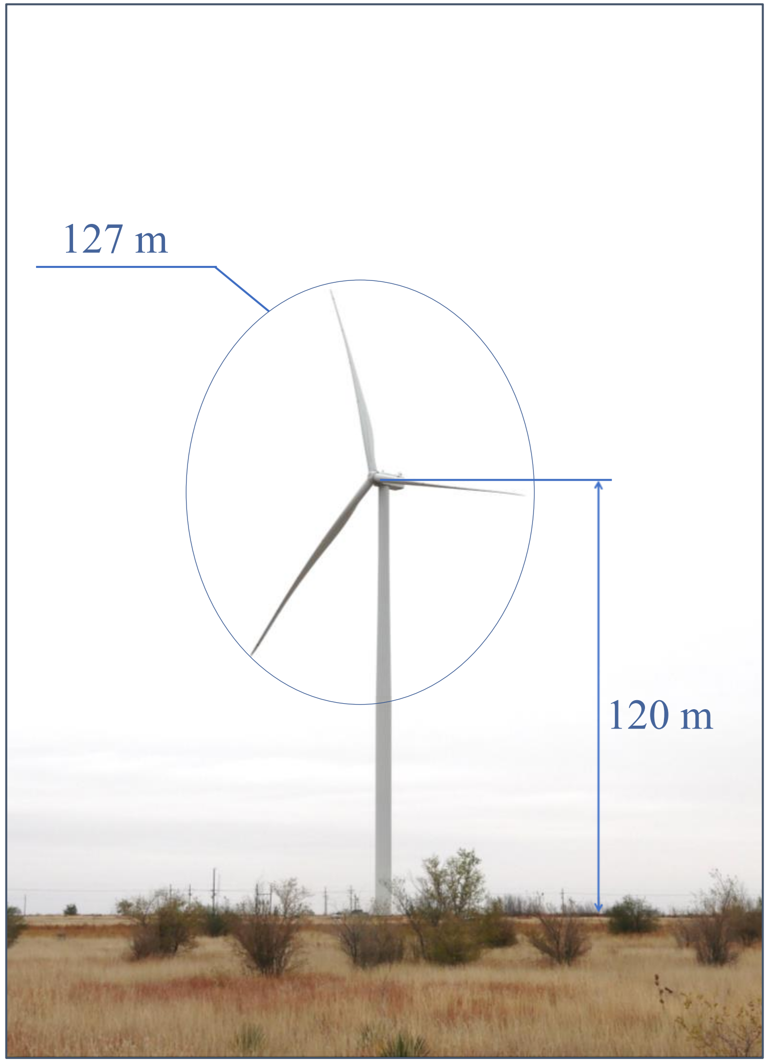
Intro to P3 Turbine

Overview:

- Model: GE 2.8 MW
- Built: 2018
- Location: Lubbock, TX

Data channels considered:

- Yaw
- Blade pitch
- Rotor speed
- Power
- Blade root strain (flapwise and edgewise)



Modeling Approaches

<u>OpenFAST v3.2</u>

- AeroDyn
  - BEMT wake/induction model
  - Blade divided into 48 sections, and airfoil data derived from wind tunnel tests by GE including corrections for rotational augmentation between blade root and 30% span
    - Unsteady airfoil aerodynamics are disabled
  - Tower potential field and shadow are ignored

- BeamDyn
  - Tuning of the geometrically-exact beam model implemented in BeamDyn was performed to match measured natural frequencies and damping on the blade (tuning also performed on Euler-Bernoulli beam model implemented in ElastoDyn for comparison)
  - Initial blade pitch and RPM specified from measurement

- ServoDyn
  - The Reference Open-Source Controller (ROSCO) [4] was implemented through ServoDyn and tuned to match the transient behavior and peak loading in the field controller

[4] Nikhar J Abbas, Daniel S Zalkind, Lucy Pao, and Alan Wright. A reference open-source controller for fixed and floating offshore wind turbines. Wind Energy Science, 7(1):53–73, 2022.

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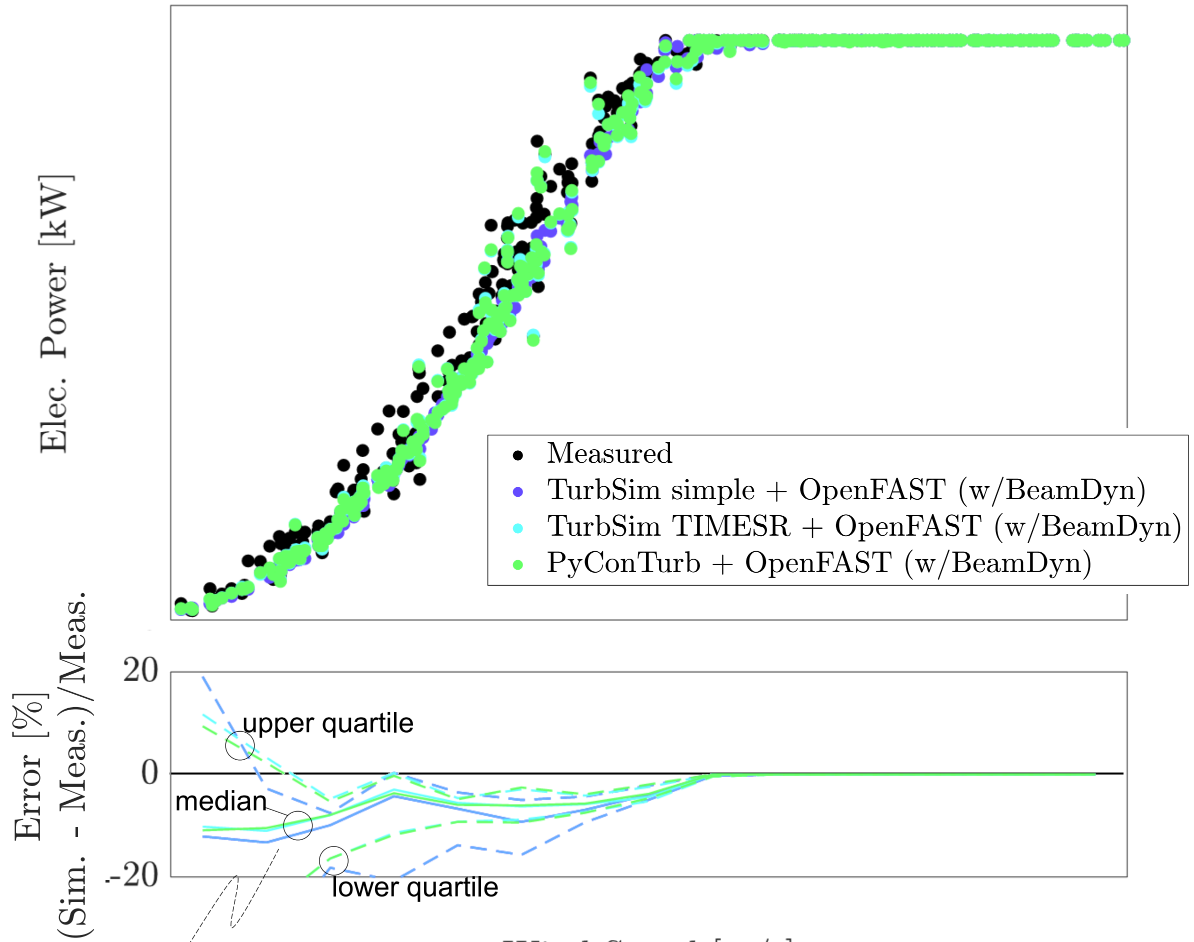
Results

QoI: Power

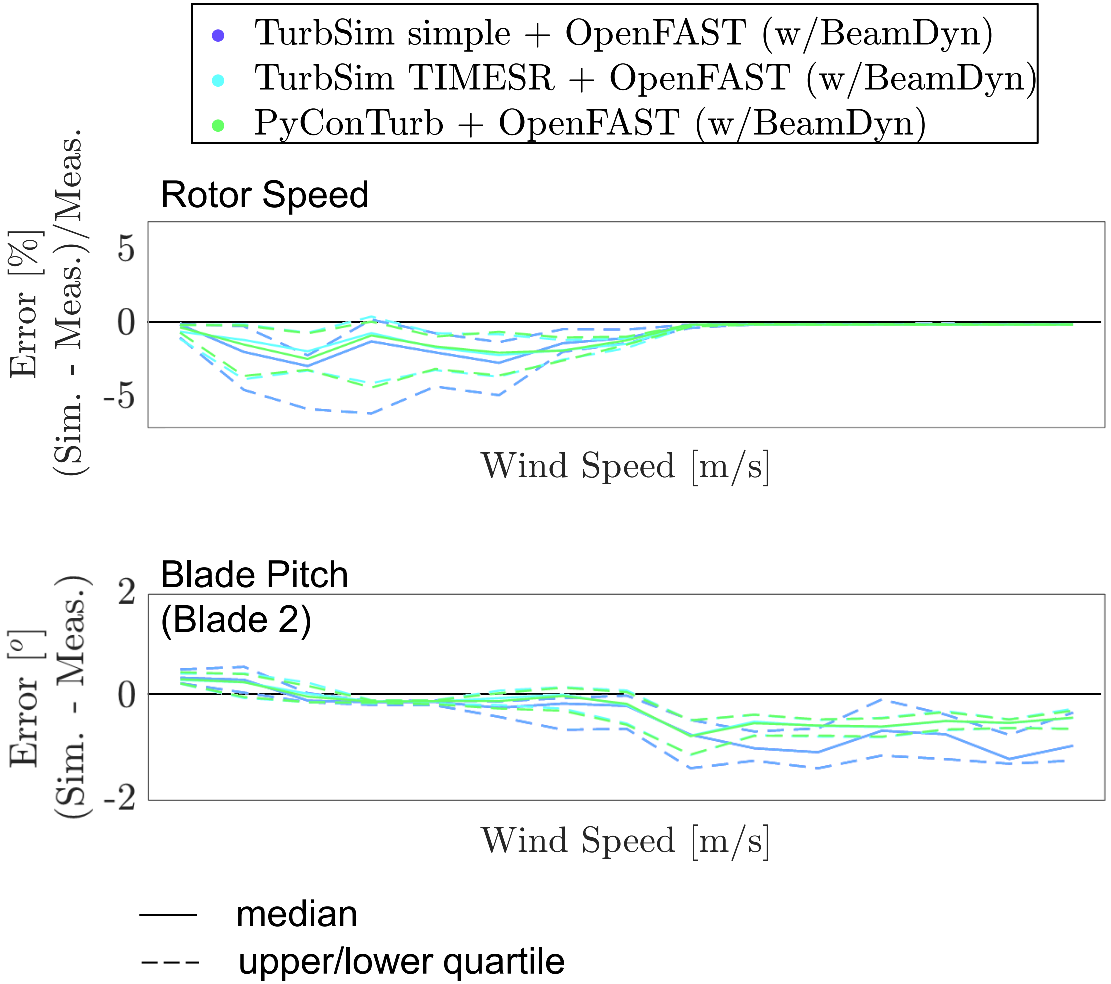


Statistics calculated by grouping the individual errors into bins of width 1 m/s

- A number of experimental outliers are not replicated by the simulations and could be a result of modeling error in the inflow, turbine, or controller logic
- The reason for the overall underprediction of power in Region II is not yet known
- It is difficult to extract ranking of the models, though the two higher fidelity approaches stand apart from *TurbSim simple* with improved median absolute deviation of power:
  - TurbSim simple: 2.4%
  - TurbSim TIMESR: 1.7%
  - PyConTurb: 1.4%

Results

QoIs: Rotor Speed and Blade Pitch

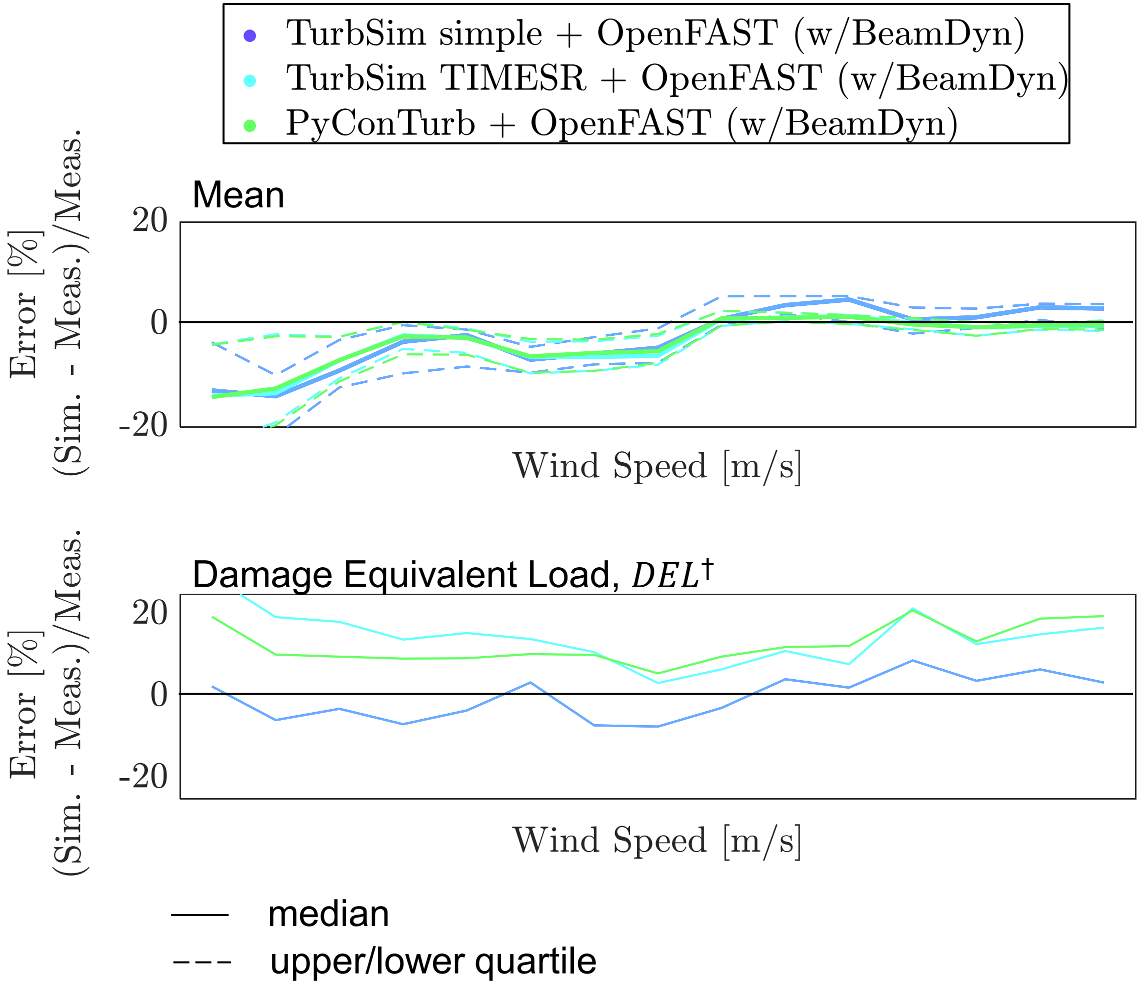


- Rotor speed errors generally mirror power errors
- Rotor speed error is not very sensitive to the inflow generation model

- All models underpredict pitch above rated, especially TurbSim Simple
- Basic operability of the turbine model has been established

Results

QoI: Root Flapwise Bending Moment*
(Blade 1)



*Simulated data is in floating coordinate system local to the deflected beam ("MyL" in BeamDyn) and interpolated to spanwise position of strain gauges

†10-minute DEL are calculated with a modification of MCrunch [5] (i.e., Palmgren–Miner damage accumulation combined with S–N curve characterizing the material fatigue performance).

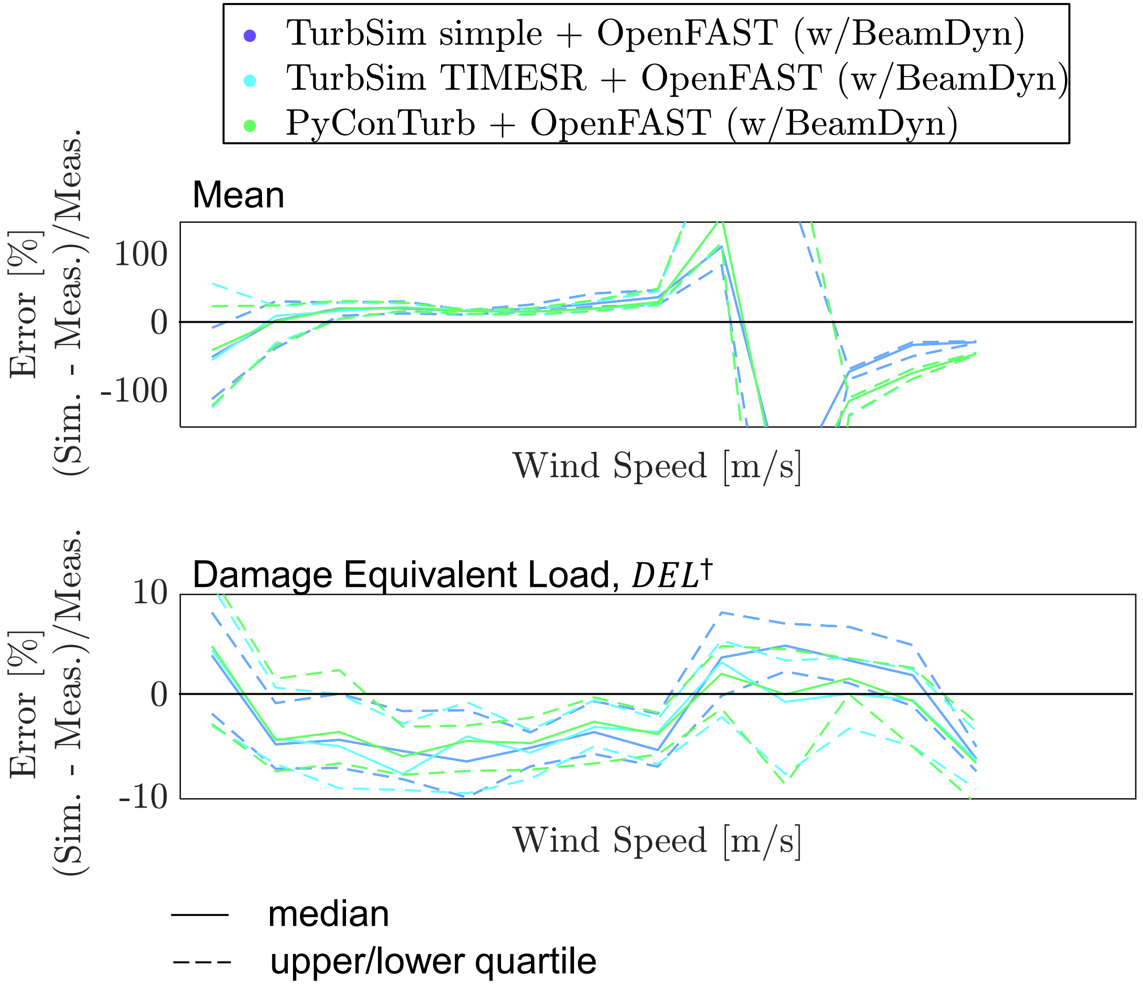
- Mean flapwise loading error shares same pattern as power curve in Region II and is underpredicted by up to ~14%
- Little spread between the quartiles indicates a fairly consistent bias

- TurbSim Simple, which uses the detrended hub-height wind speed to calculate turbulence intensity, shows best predictions with error never worse than 9% for any wind speed bin
- Time-resolved inflow generators overpredict the flapwise DEL compared to the measurement – why?
  - Overprediction was still present in Region II with unsteady aerodynamics included
  - Overprediction is relatively constant with turbulence level, as well as with wind speed

[5] Buhl, Marshall L. *MCrunch user's guide for version 1.00*. Denver, CO: National Renewable Energy Laboratory, 2008.

Results

QoI: Root Edgewise Bending Moment*
(Blade 1)



*Simulated data is in floating coordinate system local to the deflected beam ("MxL" in BeamDyn) and interpolated to spanwise position of strain gauges

†10-minute DEL are calculated with a modification of MCrunch [5] (i.e., Palmgren–Miner damage accumulation combined with S–N curve characterizing the material fatigue performance).

- More than half of the selected bins suffer from an obvious offset for all blades; these bins removed
  - The 159 remaining bins correspond to a 10 day period in September, 2021
- Remaining data shows ~20% overprediction in Region II, though the absolute magnitude of error is not severe

- Root edge bending DEL is underpredicted by ~5% in Region II, and the two higher-fidelity inflow generators generally produce better results beyond rated

[5] Buhl, Marshall L. *MCrunch user's guide for version 1.00*. Denver, CO: National Renewable Energy Laboratory, 2008.

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Summary/Plan Forward

64 hours of meteorological data have been ingested and assimilated into three turbulence generation routines

An implementation of OpenFAST was developed in coordination with GE to match a 2.8 MW turbine

Validation results indicate that the power curve and basic operability are fairly well predicted by the turbulence codes + OpenFAST without much sensitivity to the method of turbulence generation

Some larger discrepancies are found in the DELs – **the cause(s) of this are still under investigation**

Further work:

- Investigate effect of unsteady aerodynamics module on turbine stability
- Look at spectral content of measured vs simulated strain data?