Sandia National Laboratories

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# Wind turbine blade load characterization under yaw offset at the SWiFT facility


PRESENTED BY

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ENERGY NNSA

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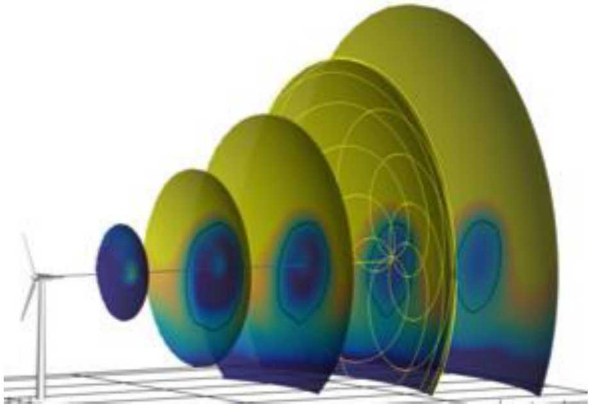
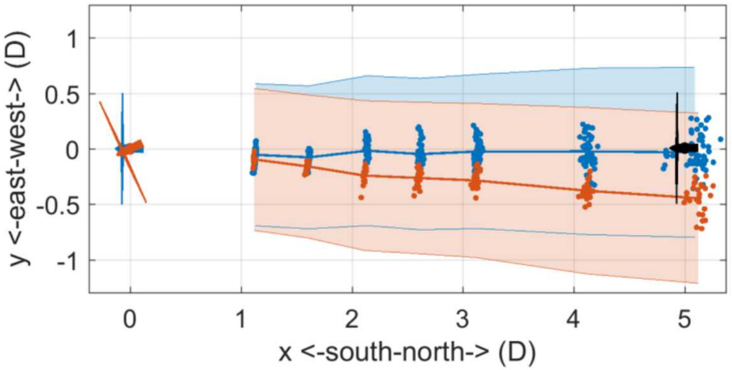
# Introduction

- Wind turbines operate in stochastic flow environments with constantly changing wind speed and direction
- Yaw systems are designed to respond slowly to not over-exercise their components meaning wind turbines nominally operate with an unintentional yaw offset
- There has been recent interest in intentionally yawing wind turbines out of the wind as a wind plant control strategy to improve system power benefits
- For both intentional and unintentional yaw offsets, there is a need for better understanding of the effect on fatigue loads to improve the operation of future wind plants

# Introduction

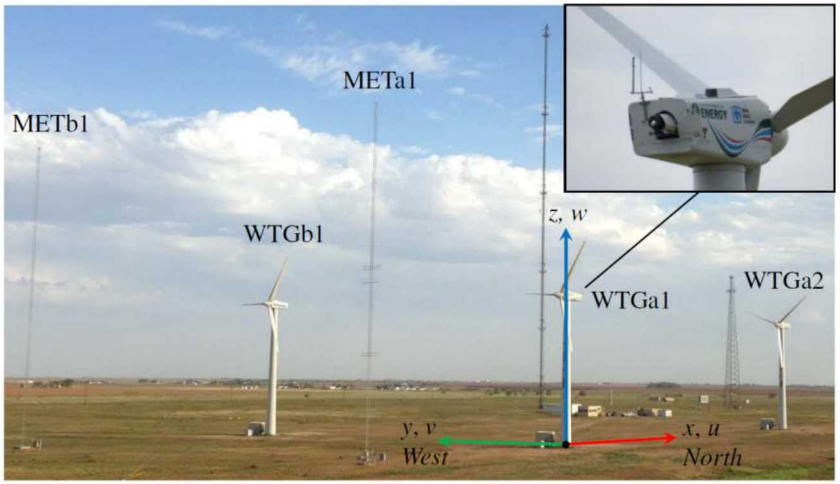
- Research has been performed on intentionally yawing wind turbines out of the wind at the DOE/SNL Scaled Wind Farm Technologies (SWiFT) facility during the summer of 2017
- The Wake Steering Experiment was performed in collaboration with the National Renewable Energy Laboratory as part of the U.S. Department of Energy's Atmosphere to Electrons (A2e) program
- The experiment includes data from an upstream meteorological tower, two wind turbines spaced 5-diameters apart, and the DTU Spinner Lidar scanning the wake behind the dominantly upstream turbine

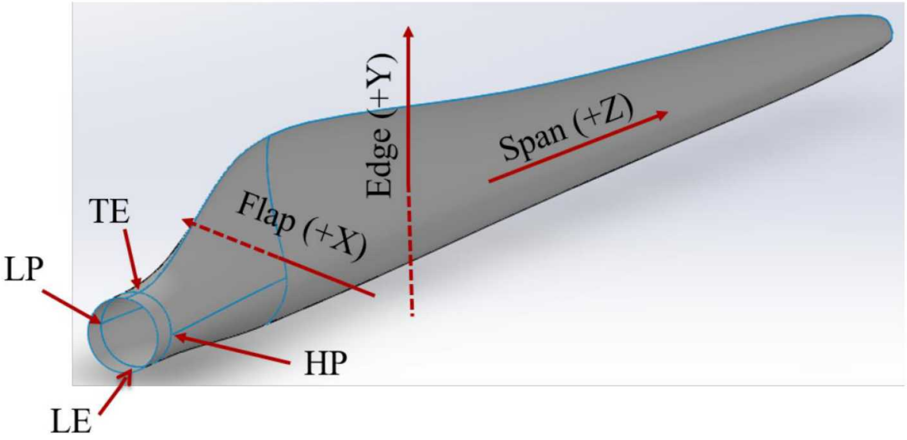




# Methods

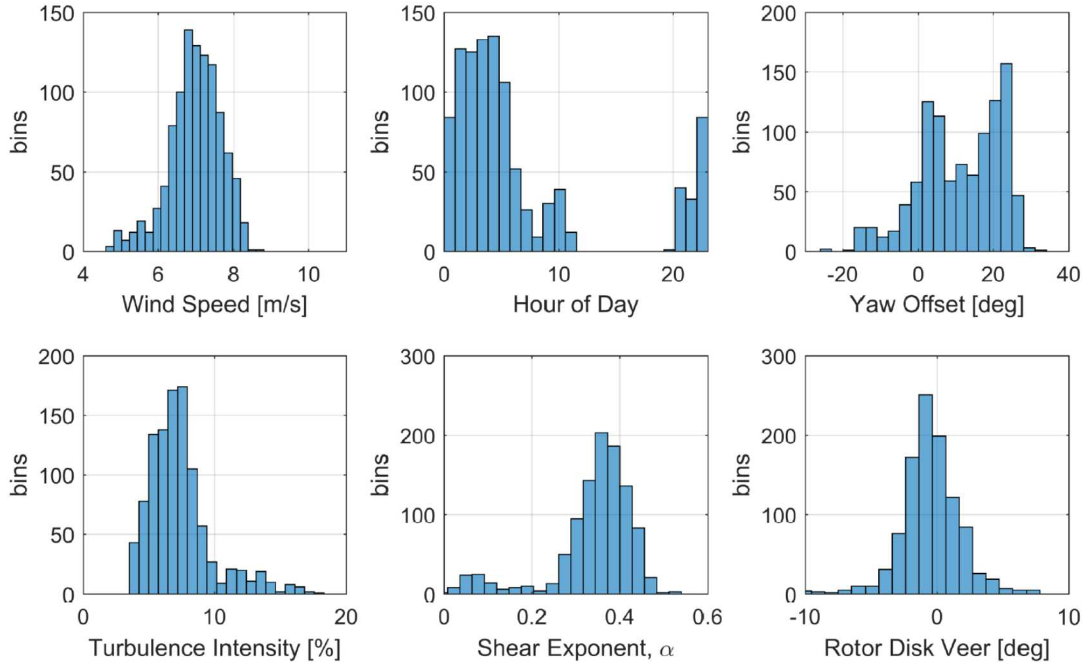
- Data acquired from WTGa1 and METa1 between July 9-13, 2017 are used in this analysis.
- Data are sampled at 50 hz and logged with a site GPS time.
- WTGa1 analyzed data include:
  - optical blade root strain gage pairs calibrated to blade root flapwise and edgewise bending moments
  - generator electrical power output
  - wind turbine azimuth position and rotational speed
  - nacelle heading
- METa1 analyzed data include:
  - sonic anemometer measured wind speed/direction at 5 tower heights



# Methods

- Data are separated into 50-rotation bins (70-150 sec)
- Data are filtered for a minimum power threshold, operation in Region 2, and for unobstructed wind directions
- Due to the campaign objectives the data are biased towards high shear, low turbulence conditions with positive yaw offset
  - Bulk data trends are biased towards high shear and low turbulence compared to the site averages for the shear exponent of 0.21 and turbulence intensity of 12%



# Methods

**Rotational Spectral Analysis:**

- Operational loads data are processed through a rotational Fourier analysis
- Data are separated into 50-rotation bins and resampled into evenly discretized 15° azimuth positions
- Amplitude and phase frequency content is calculated for each bin at per-revolution (P) forcing's

$$X_k(\omega_\theta) = \Sigma_{n=1}^{N} x(\theta) e^{\frac{-i2\pi(k-1)(n-1)}{N}}$$

**Fatigue Calculations:**

- Blade load fatigue cycles are extracted through rainflow cycle counting of the first 60-sec from the 50-rotation bin's time series
- Damage equivalent loads (DEL) for the flapwise and edgewise root bending moment are calculated and compared as ratios to a reference DEL
- A fatigue slope of m=10 for fiberglass is used
- The increase in blade damage (D) caused by the operational conditions is the normalized DEL raised to the fatigue slope (m=10)

$$M = M_u \cdot N^{-1/m}$$

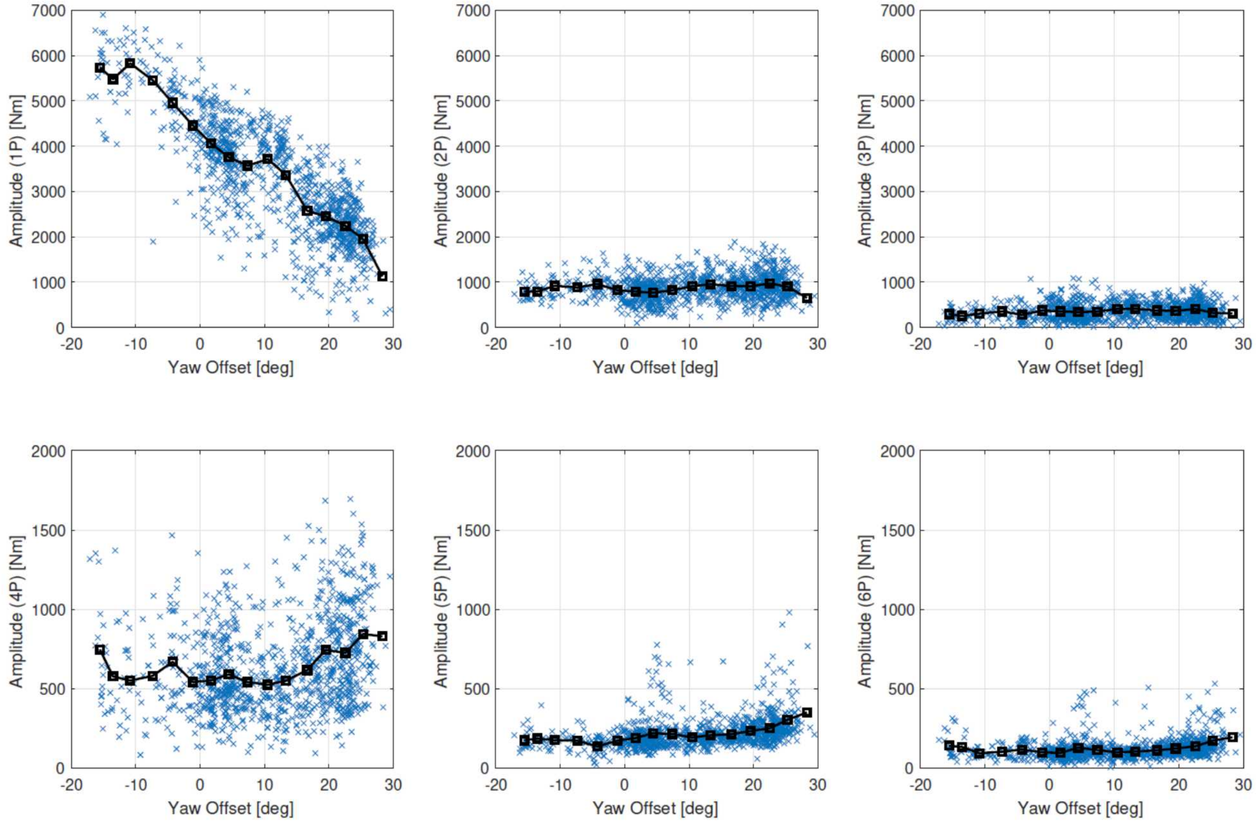
$$M_e = \frac{M_a}{1 - \frac{M_m}{M_u}}$$

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i}\bigg|_{M_{e,i}}$$

$$DEL = M_u \left(\frac{10^6}{D}\right)^{-1/m}$$

$$\frac{D_2}{D_1} = \left(\frac{DEL_2}{DEL_1}\right)^m$$

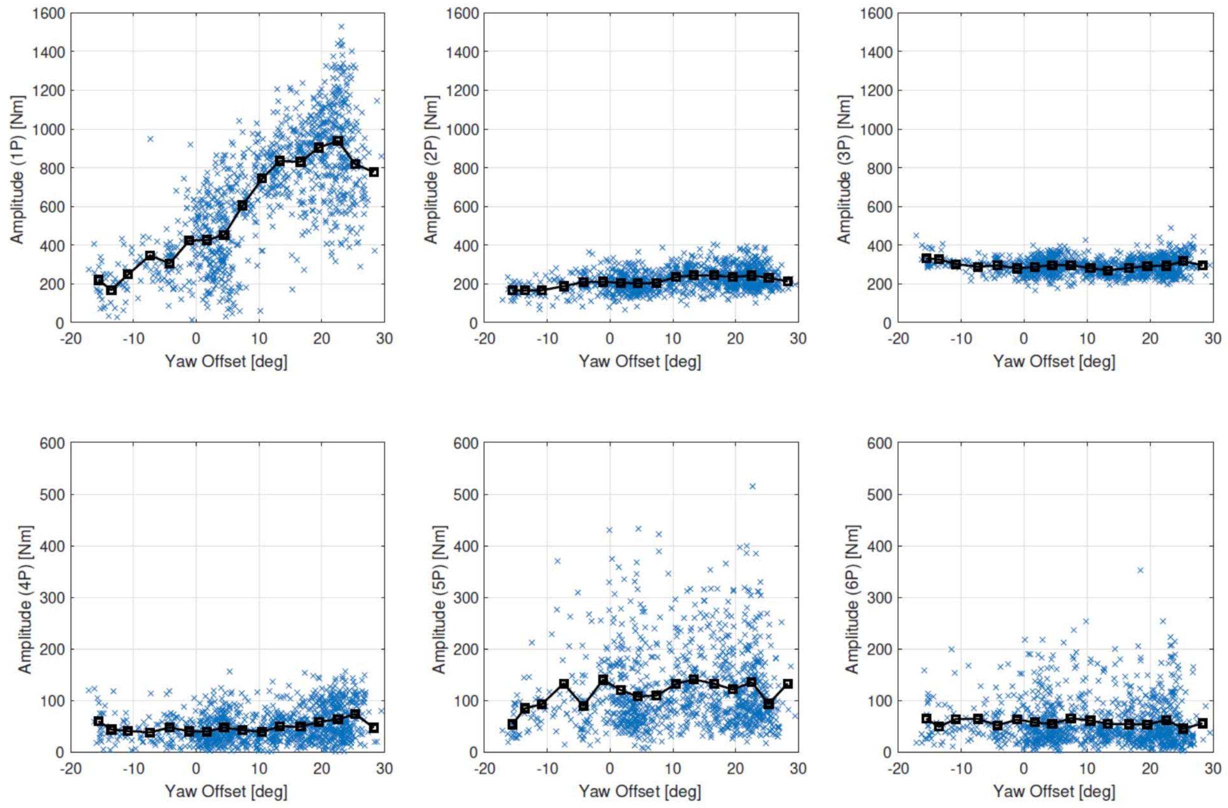
# Experimental Results




(a) Rotational spectral analysis flapwise bending moment amplitude content

- Strong, negative correlation between 1 per-revolution amplitude and yaw offset for flapwise bending moment
- 2-6 per-revolution amplitude content are uncorrelated with yaw offset

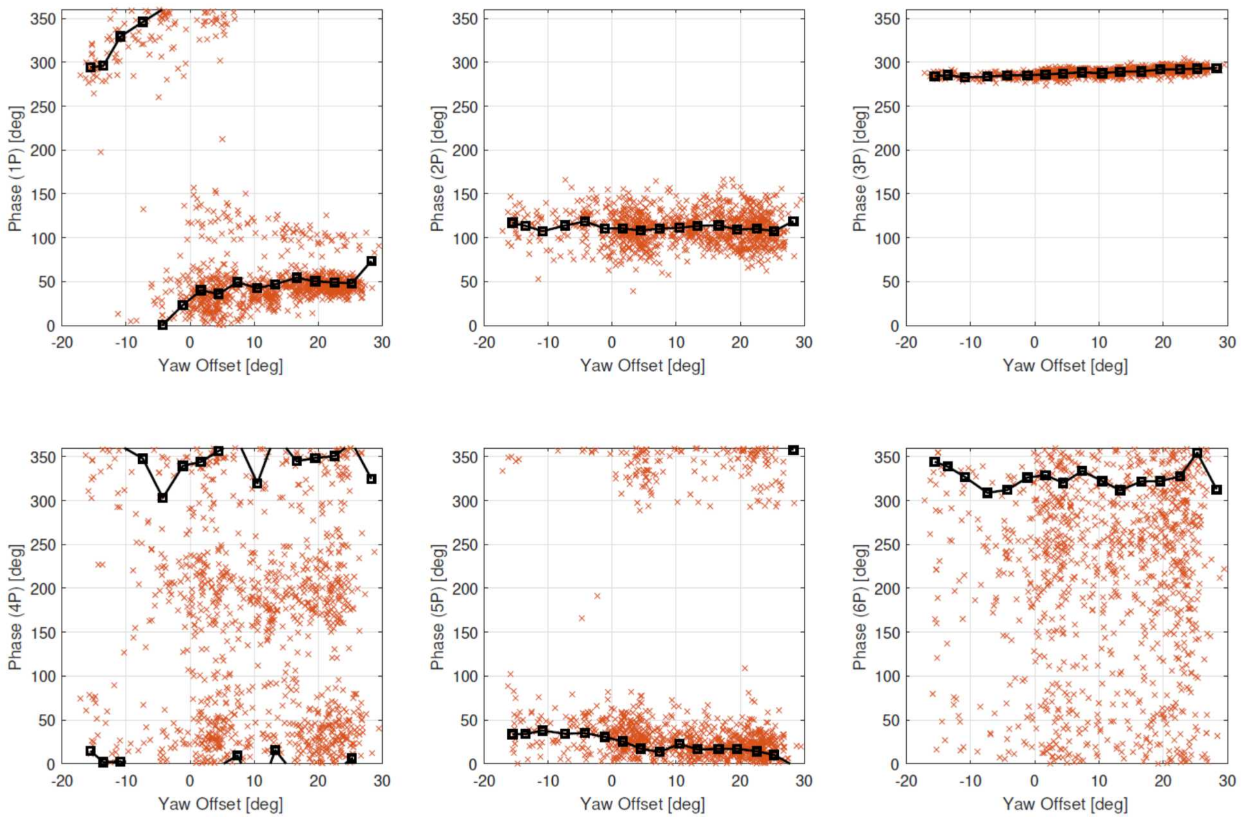
# Experimental Results




(a) Rotational spectral analysis edgewise bending moment amplitude content

- Strong, positive correlation between 1 per-revolution amplitude and yaw offset for edgewise bending moment
  - The 1P amplitude correlations show opposite trends for flapwise and edgewise bending moments
- 1P amplitude is best signal to track for yaw offset identification

# Experimental Results

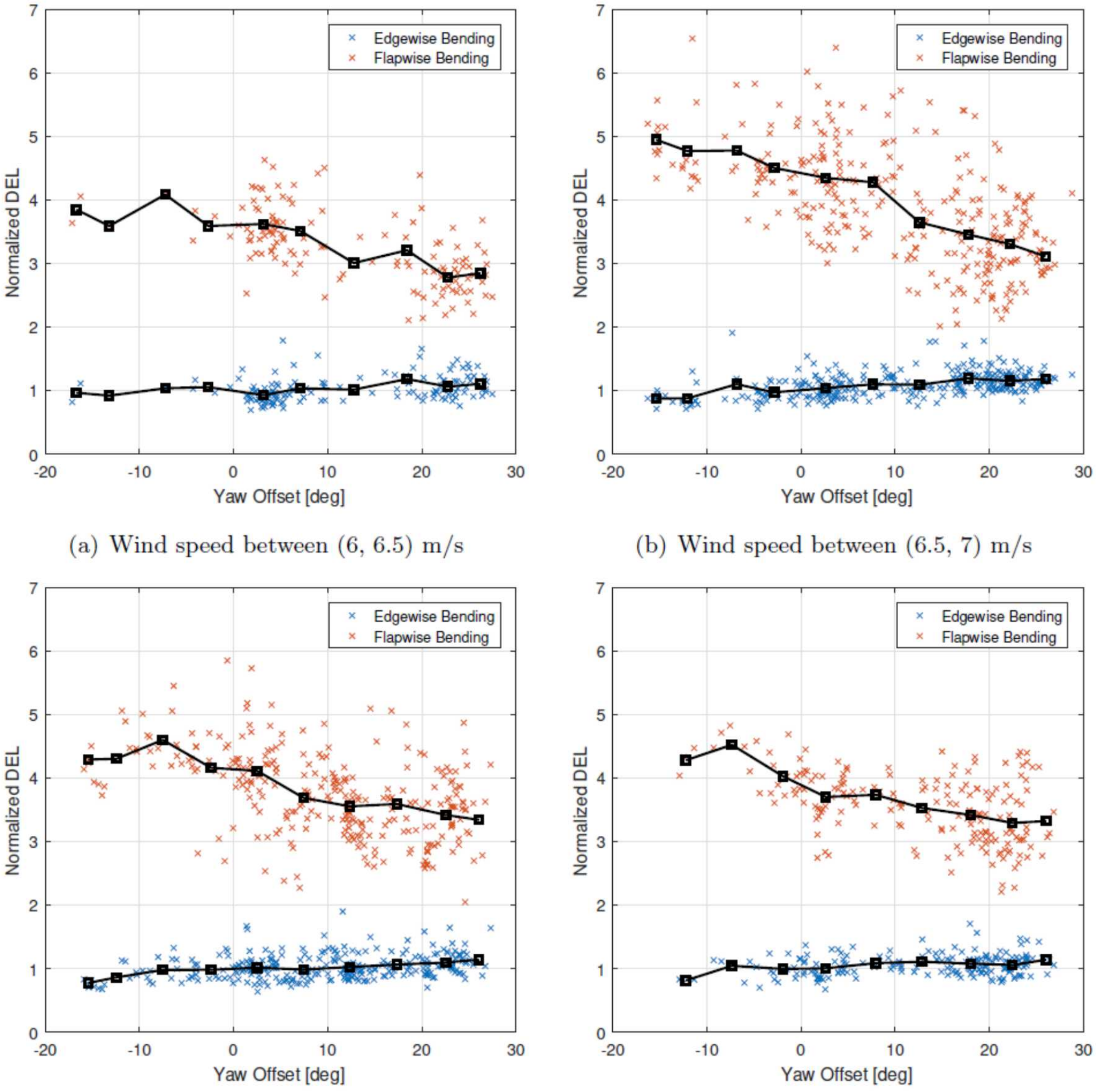



(b) Rotational spectral analysis edgewise bending moment phase content (wrapped from 0° to 360°)

- Phase content for flapwise and edgewise bending moments show weak correlations with yaw offset which typically are within the data's spread
- 1P edgewise phase is most strongly correlated, where the phase angle moves towards the downstream portion of the rotor with yaw offset
- 1P flap- and edgewise phase angle are only equal at a -10° yaw offset

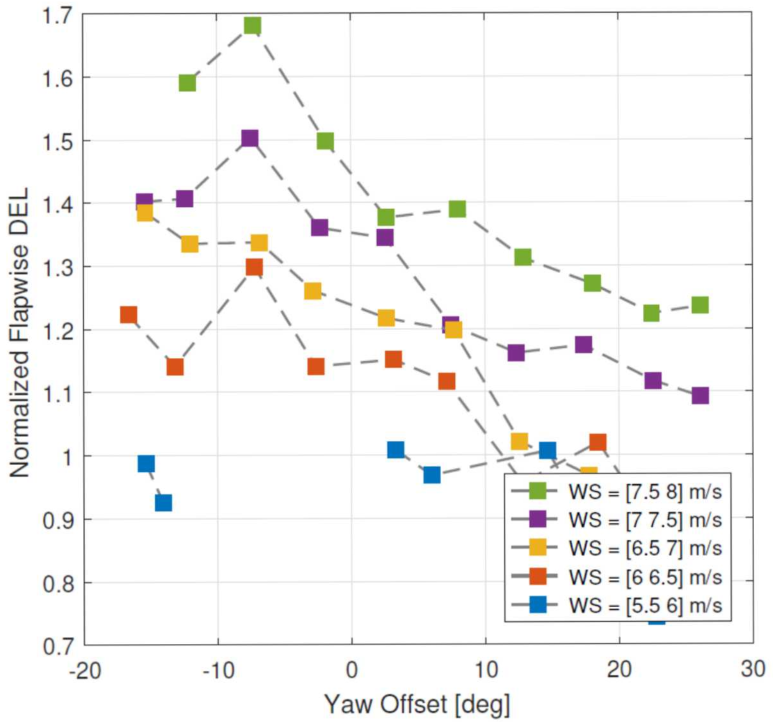
# Experimental Results

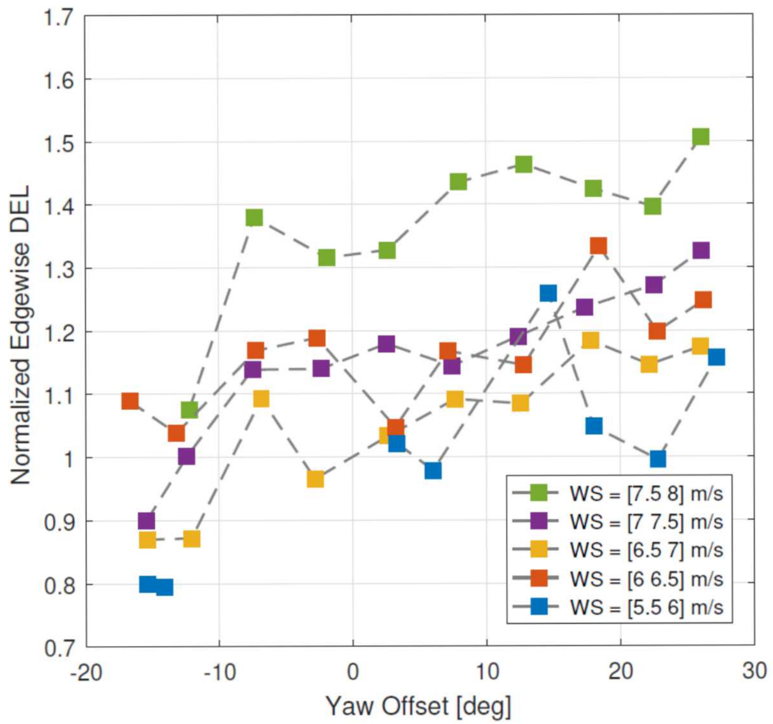
- Damage equivalent loads are calculated for each bin and normalized by the edgewise DEL at zero yaw
- The effect of wind speed on DEL can be more substantial than yaw offset so the data are further grouped into 0.5 m/s bins
- Bin averages are calculated for every 5° yaw offset bins
  - The lowest wind speed bin (a) has insufficient negative yaw data so its trend for negative yaw should be disregarded



(a) Wind speed between (6, 6.5) m/s
(b) Wind speed between (6.5, 7) m/s
(c) Wind speed between (7, 7.5) m/s
(d) Wind speed between (7.5, 8) m/s

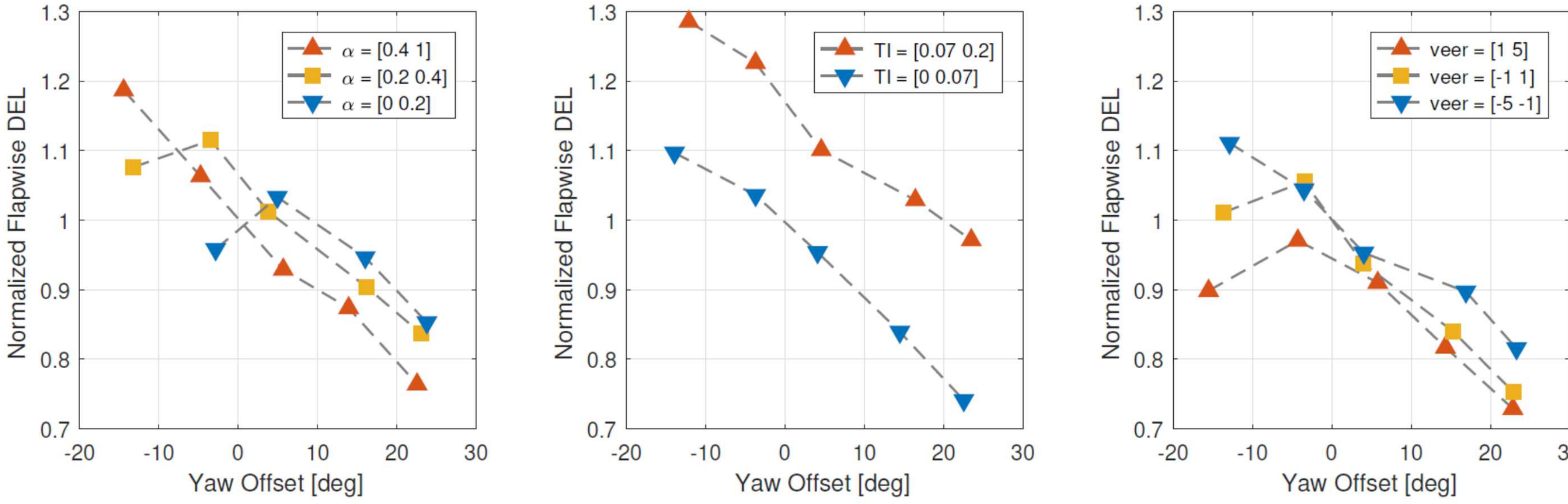
# Experimental Results




- The correlation of DEL with wind speed is seen to be as substantial as the yaw offset
- Data reveals that flapwise DEL increases with negative yaw and decreases with positive yaw as the velocity shear loading is balanced
- Edgewise DEL shows the negative trend that was observed in the 1P amplitude content, but with a shallower slope

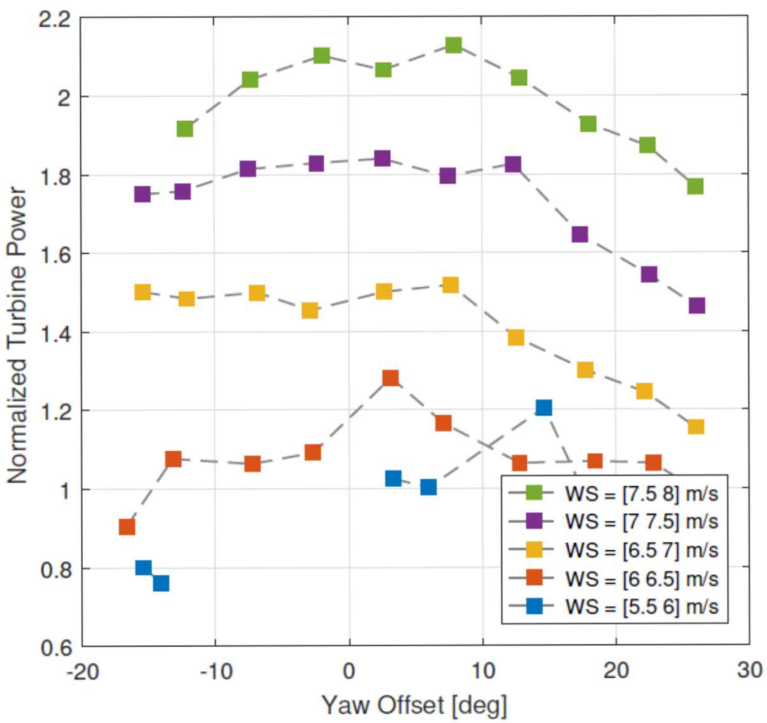
# Experimental Results

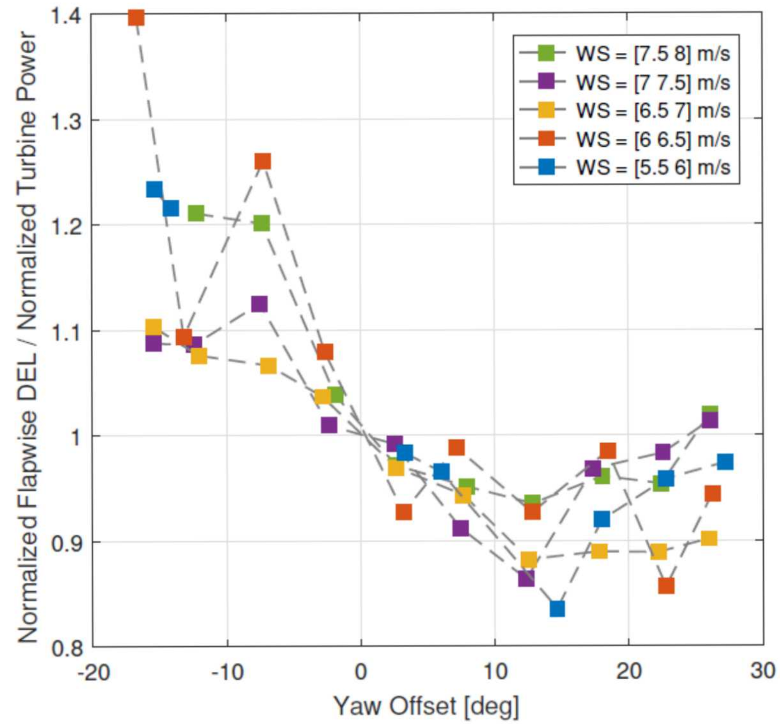



(a) Velocity shear DEL trends (b) Turbulence intensity DEL trends (c) Wind veer DEL trends

- The data are further divided into atmospheric states including all of the wind speed data from 6-8 m/s to ensure sufficient data content
- In positive yaw, the DEL for low shear cases decreases at a lower rate than high shear cases, as expected
- Turbulence intensity has a stronger observed effect than shear
- Wind veer is not strongly correlated, although for positive yaw negative veer appears to increase DEL while positive veer decreases DEL

# Discussion




- Yaw offset is observed to reduce power beyond around ±10°
- Yaw offset reduces power and alters the fatigue loads for wind turbines, both negatively and positively for the SWiFT turbines
- An effective "cost" is defined which compares DEL and power, normalized to the wind speed bin's zero yaw offset values
  - For the high-shear data analyzed, the SWiFT turbine has the best overall performance at around 10-12° yaw offset

# Conclusion

- The Wake Steering experimental data were analyzed to compare blade loads with yaw offset under varying atmospheric conditions
- Flapwise bending DEL from the SWiFT turbine was observed to increase with negative yaw and decrease with positive yaw, based on the level of shear across the rotor disk
- Edgewise bending DEL has the opposite trend with yaw
- The 1P amplitude spectral content is most correlated with yaw offset, is the source of DEL increase/decrease, and may be the best signal to track to identify yaw offset magnitude
- Turbulence intensity has a stronger effect on DEL versus yaw offset than shear was observed to have
- Based on loads reduction and a relatively constant power, wind turbines may have optimal performance at a nominally positive yaw offset, based on the atmospheric conditions

The complete Wake Steering experimental dataset will be available for download at **a2e.energy.gov** by August.



## Opportunities to tour the following facilities:

- The Department of Energy & Sandia National Laboratories Scaled Wind Farm Technology (SWiFT) facility
- Texas Tech University Ka-Band Radar
- Group NIRE Distributed Energy Management
- GE Prototype Wind Turbines
- DNV-GL Lidar certification

***energyworkshops.sandia.gov***