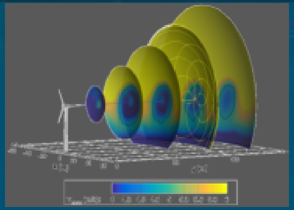
SAND2022-13190C

Sandia National Laboratories

Application of parallel-flow linear stability theory to wind turbine wakes with implications for active wake control



PRESENTED BY

Lawrence Cheung, Ken Brown, Dan Houck, Nate DeVelder, and Nicholas Hamilton

NAWEA/WindTech 2022

Sep. 20, 2022

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outline

Overview of wake control methods

- Available control vectors

Use of linear stability theory in active wake control

- Spatial analysis of shear flow instability
- Demonstration on steady inflow example

Large eddy simulation methodology

Generating a turbulent inflow

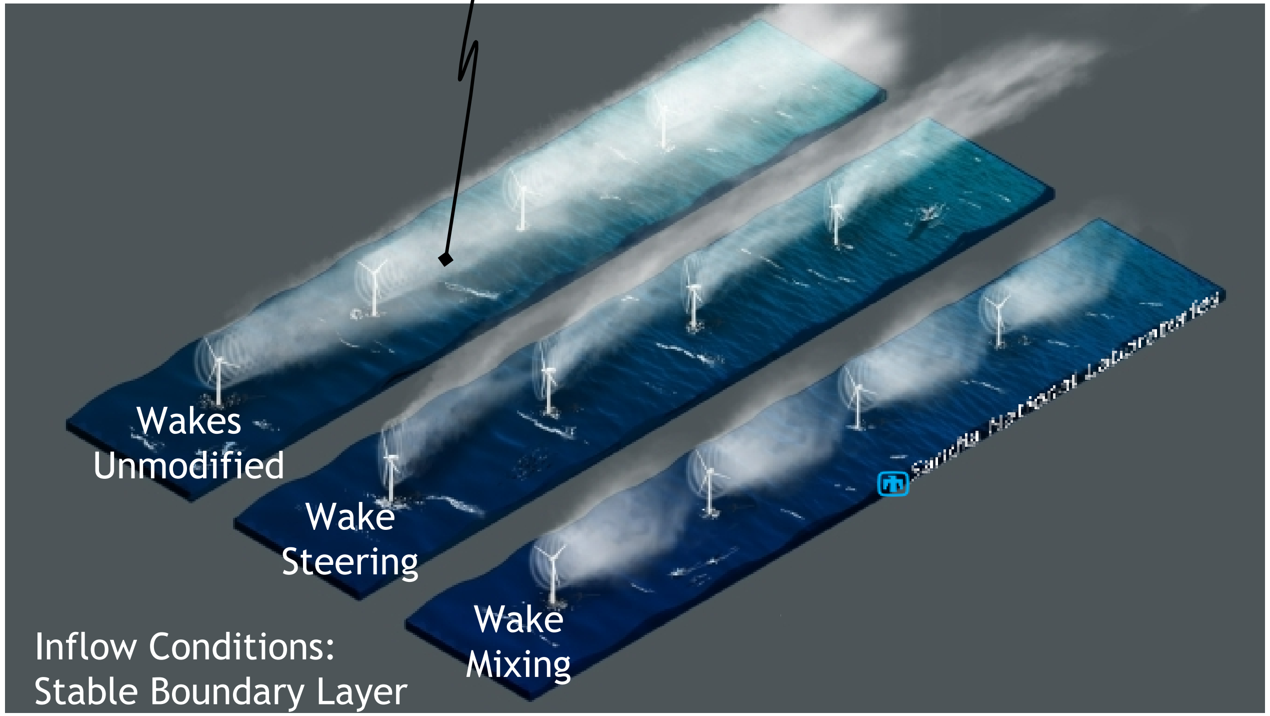
Results for turbulent inflow

- Power benefit and reliability penalty
- AEP summary

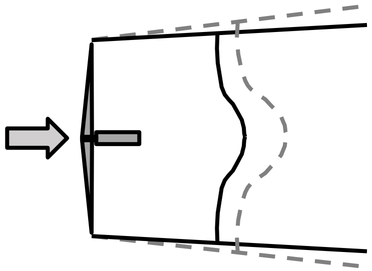
Conclusions/Future Work

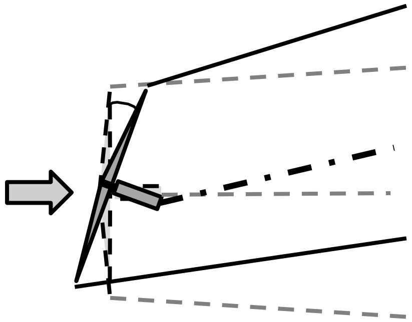
Horns Rev 2 Offshore Wind Plant

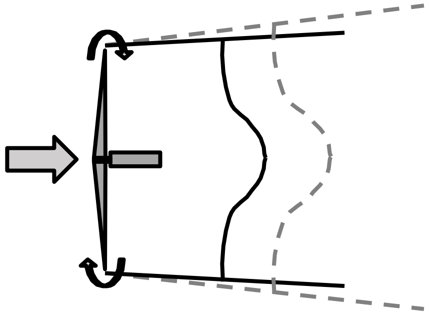
Downstream turbines engulfed in wake shadow produce less power



Overview of Existing Wake Control Techniques





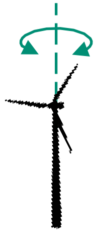


	Operating Principle	Pros	Cons
Derating	Deficit Manageme nt	Small AEP increases possible Small load reductions possible	Large power loss in controlled turbine(s) Actuation required in most turbines High uncertainty in achieving benefits Typically open-loop control
Wake Steering	Deficit Manageme nt	Small AEP increases possible Small load reductions on some turbines	Large power loss in controlled turbine(s) Actuation required in most turbines Increased loads on some turbines Difficult for tight spacing scenarios Typically open-loop control
ive Wake Control	Deficit Reenergizin g	Net power gains in deep arrays could exceed 20% Well-suited for closed-loop control with active sensing input Limited subset of turbines require actuation In deep array scenarios, power gains likely	Load increases on actuated turbine(s) Increased actuator wear (if active pitch control used)

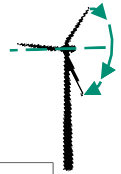
Source: Houck, DR. Review of wake management techniques for wind turbines. *Wind Energy*. 2021; 1- 26.

Control vectors for Active Wake Control (AWC)

What are possible control vectors for implementing wake control?

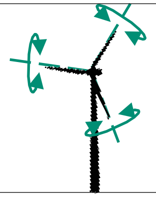


Periodic yawing: typical yaw rates of large turbines (0.3°/s for the NREL 5MW [18]) may be **too slow** to achieve meaningful oscillation amplitude needed to gain active control authority



Periodic rotor speed: generator speed control (almost instantaneous response) provides sufficient response to gain active control authority

Periodic pitching: blade pitch rates provide sufficient response to gain active control authority



↳ Our analysis considers a periodic pitching control strategy for an upstream turbine* in Region 2.5:

- Pitch control:

$$\beta = \beta_0 + \sum A \, sin(2\pi \, St_D \, U_{hub} \, D^{-1} \, t + n\theta + \phi)$$

amplitude (A), *phase* (ϕ), *dynamic pitch setting* (β), *conventional pitch set point* (β_0), *Strouhal number* (St_D), *azimuthal mode number* (n)

For example:

$\beta_0 = 0°$
$A = 0°, 1°, 2°, 3°$
$n = 0, \pm1, \pm2, \ldots$
$\phi = 0°$
$St_D = 0.3$

Question: how do we choose pitching parameters to maximize wake benefits?

* Downstream turbine uses the default control strat

Use Linear Stability Analysis to Model Large Scale Structures in Wakes

Flow disturbances at the rotor can be analyzed using Linear Stability Analysis

- Flow quantities are decomposed in terms of mean and fluctuating components

$$u(x,r,\theta,t) = \overline{U}(r,\phi) + \hat{u}(r)e^{i\alpha x + in\theta + i\omega t}$$

$$T(x,r,\theta,t) = \overline{T}(r,\phi) + \hat{T}(r)e^{i\alpha x + in\theta + i\omega t}$$

- For inviscid parallel flow, problem collapses to Rayleigh equation (Batchelor & Gill, 1962; Drazin & Reid, 1981):

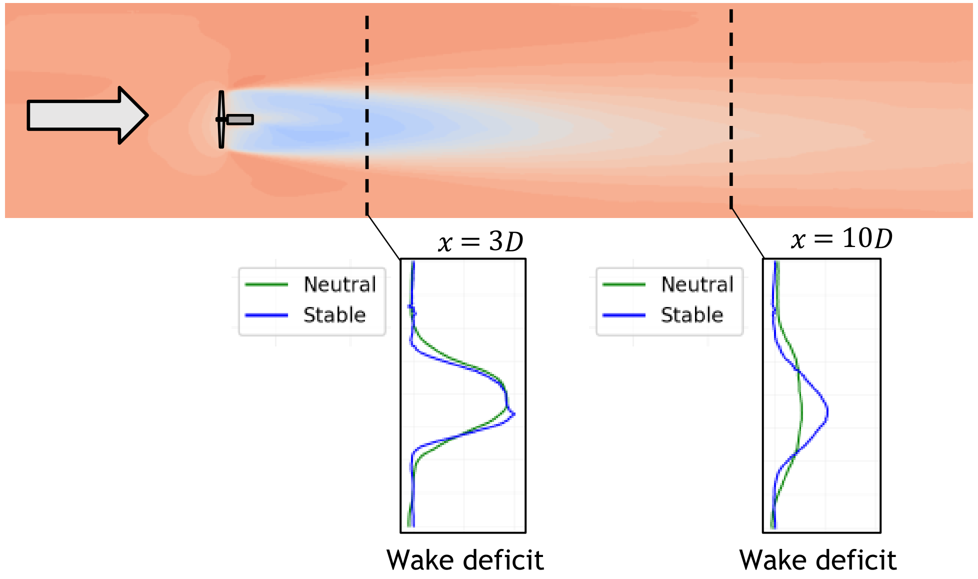
$$\frac{d^2\hat{p}_n}{dr^2} + \left(\frac{1}{r} - \frac{2}{\xi}\frac{d\xi}{dr}\right)\frac{d^2\hat{p}_n}{dr^2} - \left(\frac{n^2}{r^2} + \alpha^2\right)\hat{p}_n = 0$$

Use spatial stability analysis: disturbances grow downstream

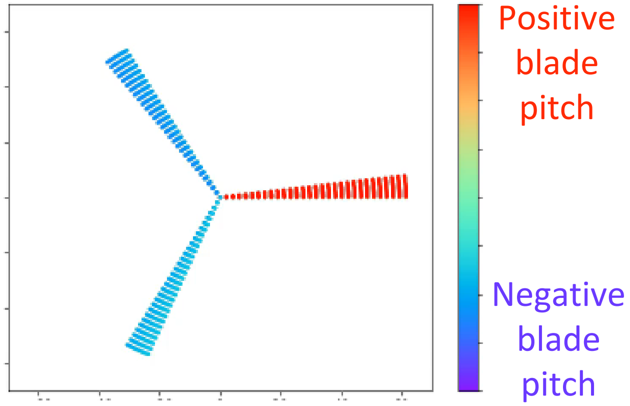
- Solve for eigenvalues $\alpha = \alpha_r + i\underbrace{\alpha_i}_{\text{growth rate}}$

Incorporate non-axisymmetric effects

- Both $\overline{U} = \overline{U}(r,\phi)$ and $\overline{T} = \overline{T}(r,\phi)$ to model inflow shear and temperature gradients with buoyancy effects
- Use asymptotic analysis for small $d\overline{T}/dz$ and $d\overline{U}/dz$ values



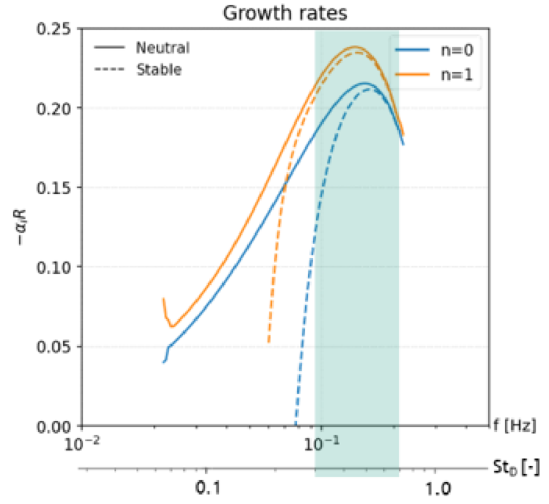
Example of AWC through pitch control with $n = \pm 1$ modes



Use Linear Stability Analysis to Model Large Scale Structures in Wakes

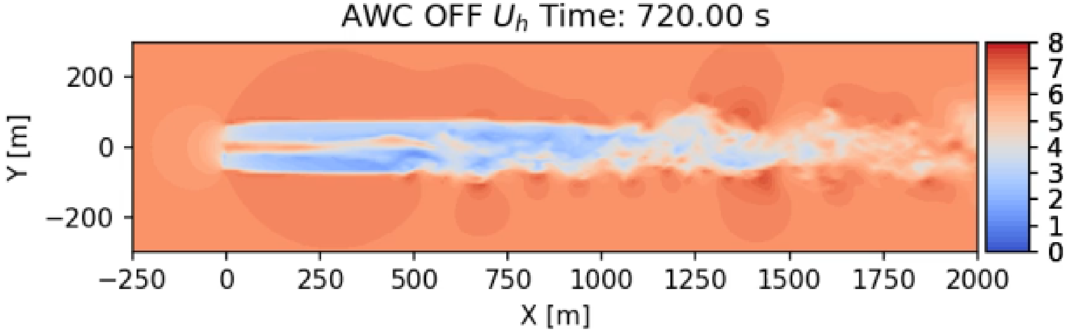
Results of stability analysis

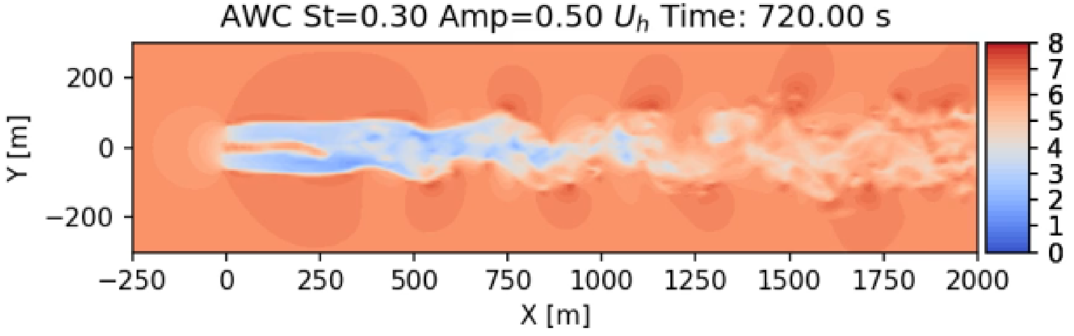
- $n = \pm 1$ and $n = 0$ modes are most unstable
- Strouhal numbers $\mathrm{St} = fD/U$ = 0.2-0.4 are dominant frequencies
- Stable stratification suppresses lower frequency modes



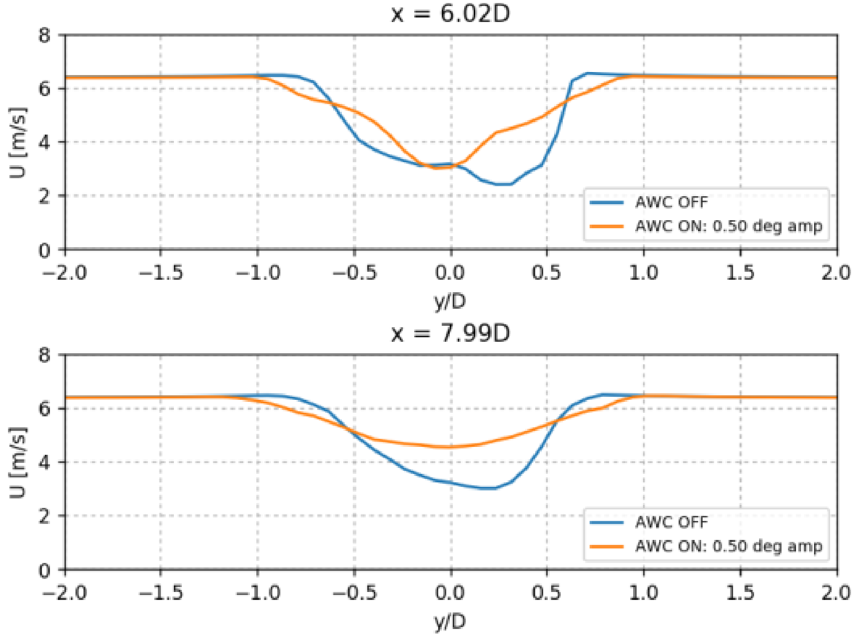
Example of AWC using IPC

- Force at St=0.30 with $n = \pm 1$ azimuthal modes
- Steady inflow with shear exponent 0.17
- AWC through IPC excites large scale structures earlier





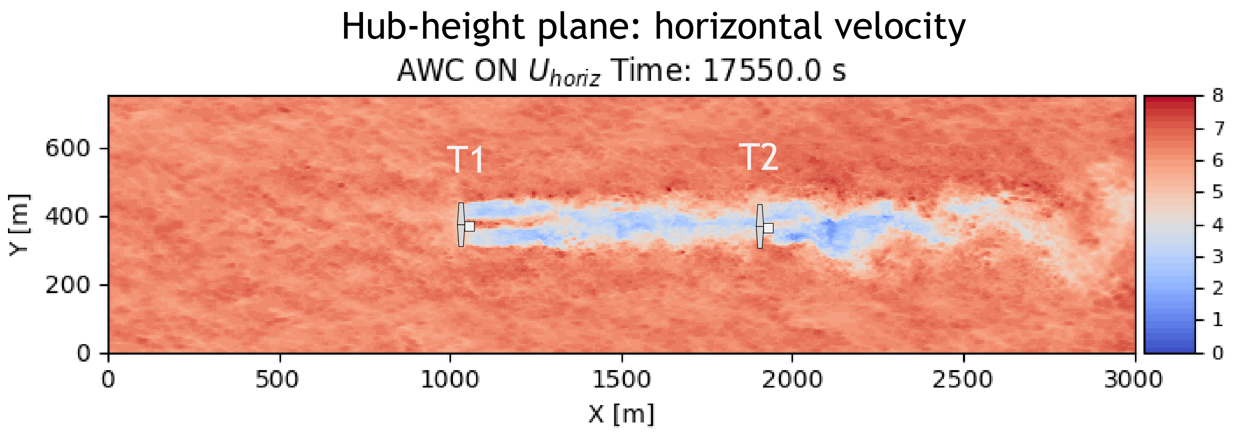
Hub-height mean wake comparison

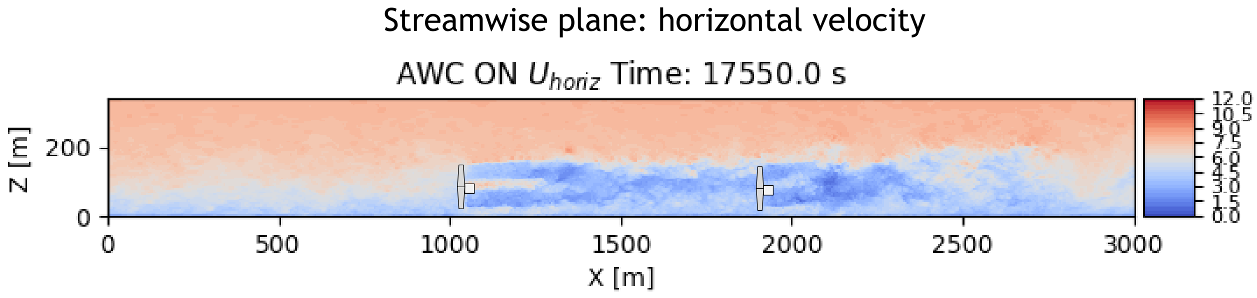


Large Eddy Simulation Methodology

<u>ExaWind/Nalu-Wind[1] Solver</u>:
- Solves incompressible Navier-Stokes with buoyancy and Coriolis forcing terms
- Unstructured finite volume LES with 1-equation k-SGS model
- Wall model BC based on Moeng (1984) and Monin-Obukhov similarity theory

<u>Turbine model & controller</u>
- Nalu-Wind coupled to OpenFAST for aeroelastic turbine simulation
- Use actuator line model (ALM) with NREL's turbine model version for GE 2.8-127
- AWC with pitch control implemented in ROSCO





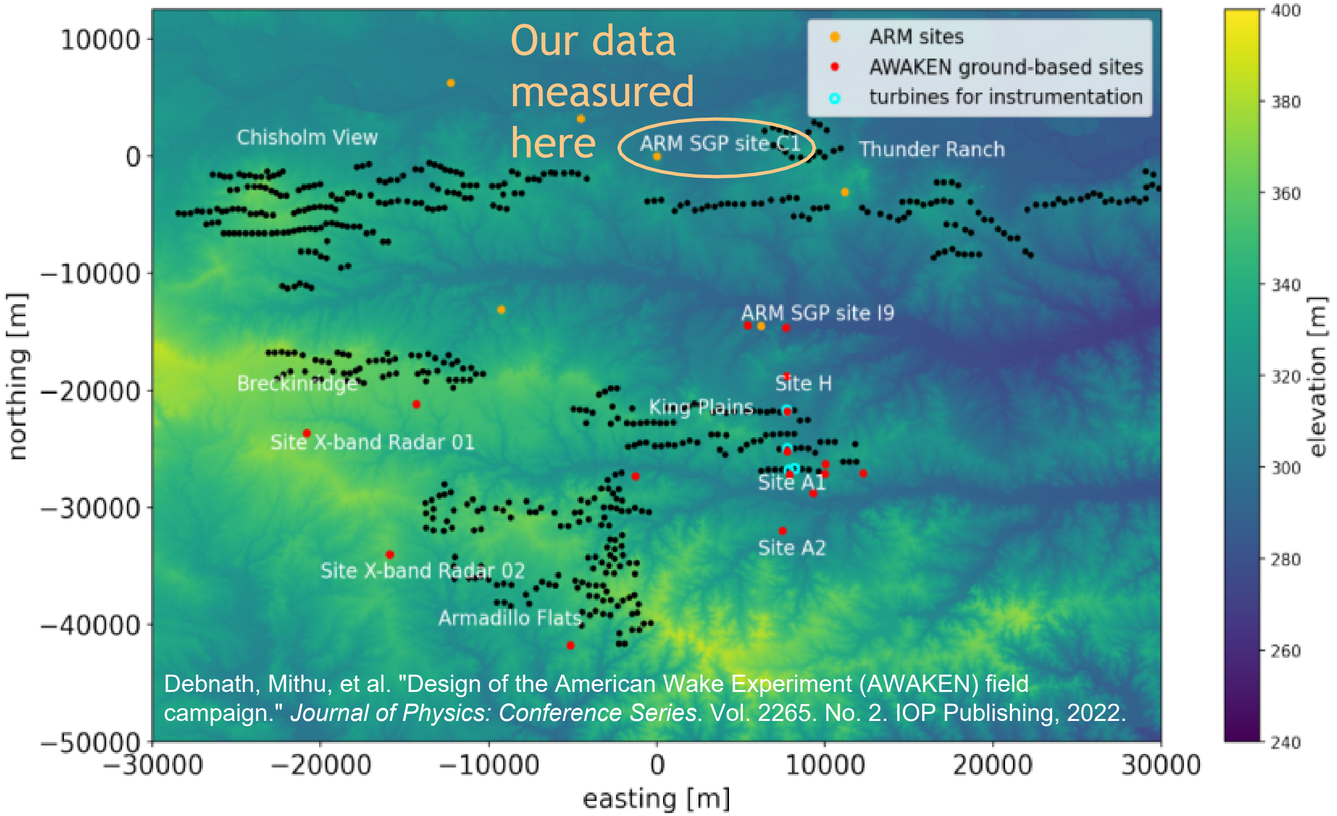
Mesh: 64M elements
Domain: 3km x 0.75km x 1km
Averaging time: 14 minutes (after transient runout)

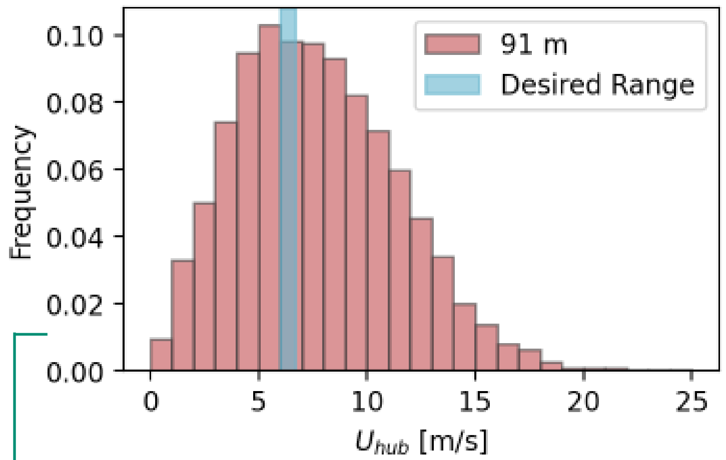
[1]http://github.com/Exawind/nalu-wind

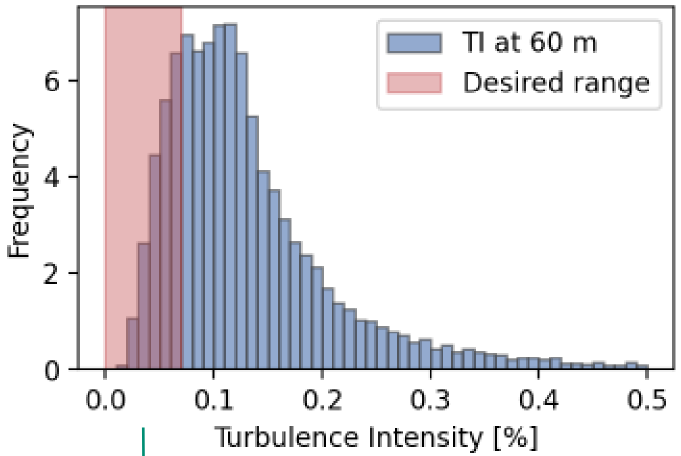
Generating a turbulent inflow

Developing a stable, Region II inflow condition to demonstrate AWC

- 10-minute bin data derives from the year 2021 from a DOE ARM facility in Oklahoma, surrounded by GE machines:



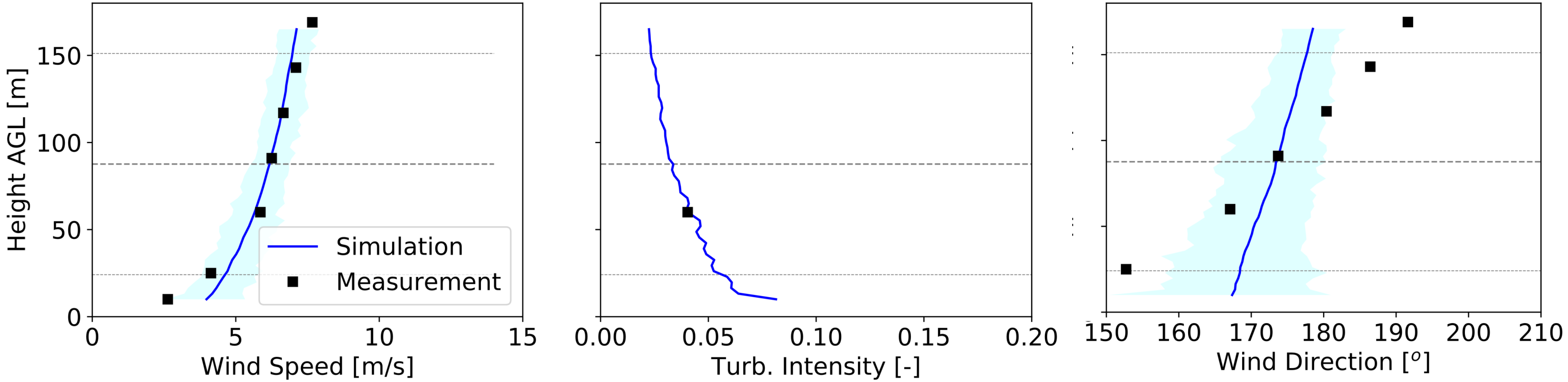




- Filters applied: wind speed (6-6.7 m/s), turb. intensity (0-7%),
- wind direction (100-260°), veer (>20°)
- 230 minutes of data meet the criteria and were used to generate the background flow

Generating a turbulent inflow

Achieved vs. target inflow conditions

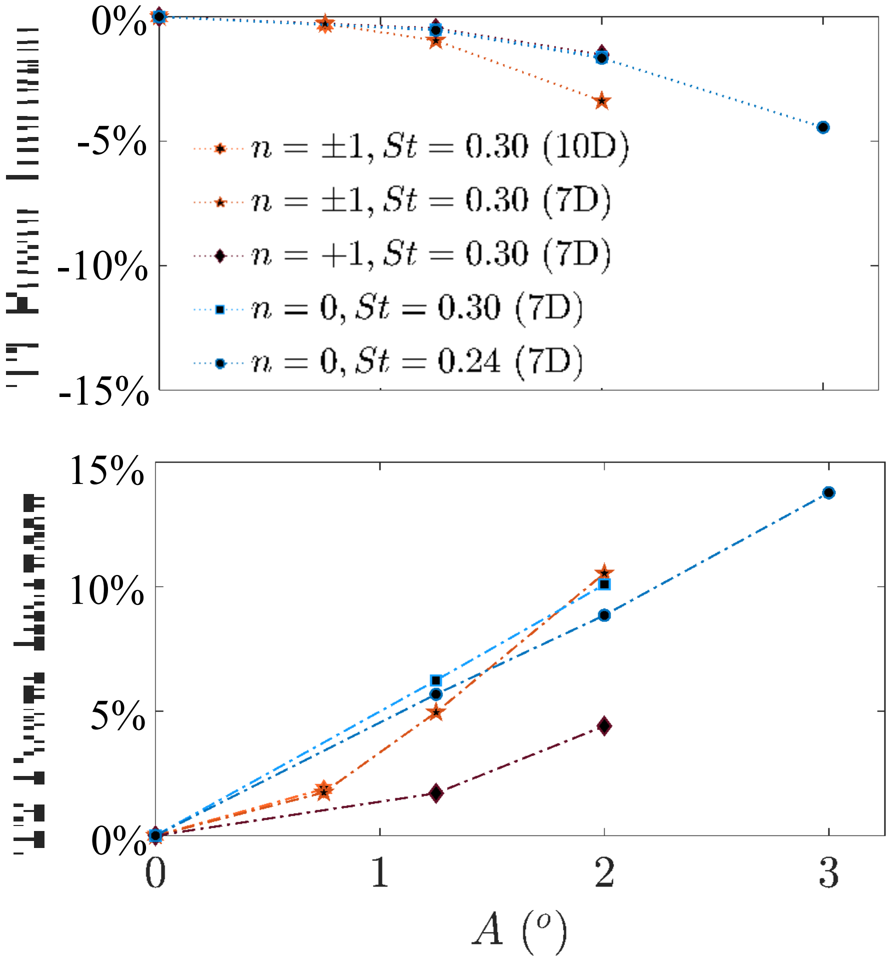


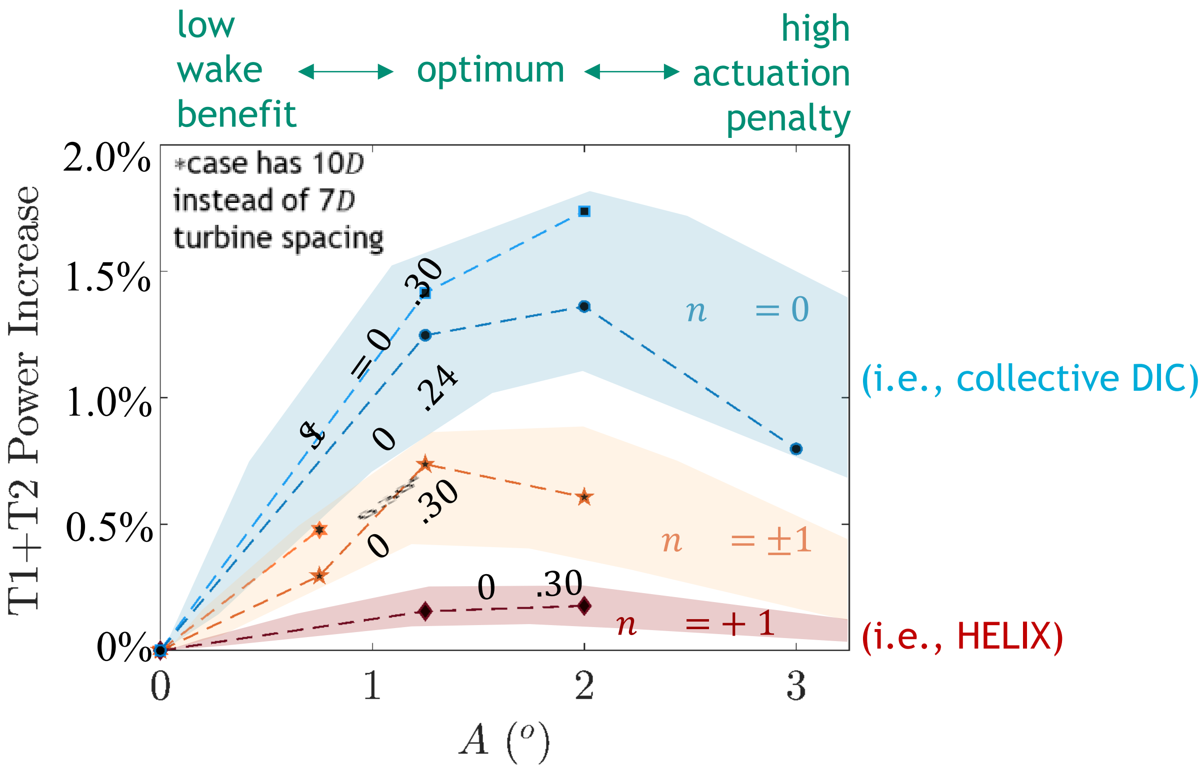
$\sqrt{2/3 * TKE}/WS$

Simulated shear and turbulence match the measurement well

Results for turbulent inflow

Power benefit



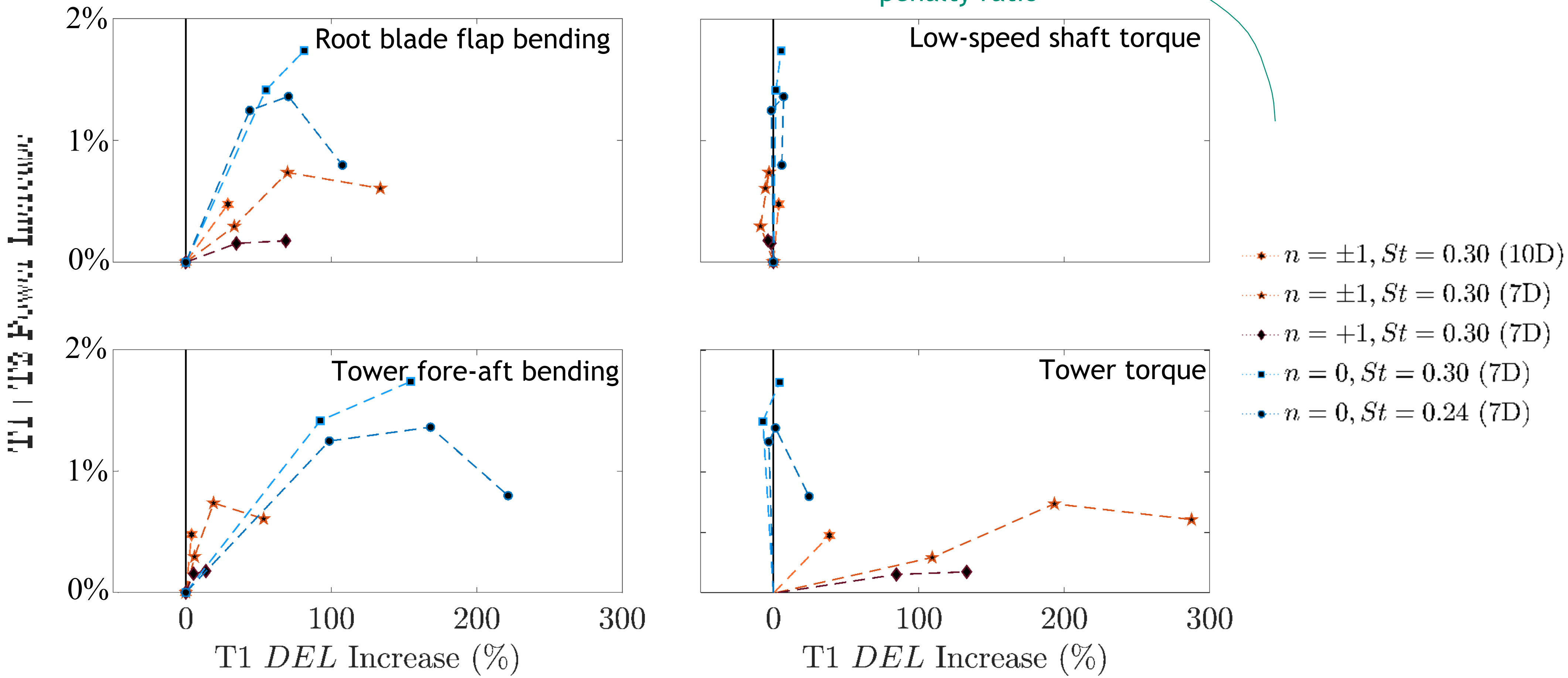


Two-turbine power increases of 1.5-2.0% likely possible in this inflow;
additional gains expected for third and fourth turbines

Results for turbulent inflow

Turbine reliability (upstream turbine fatigue)

Higher benefit-to-penalty ratio

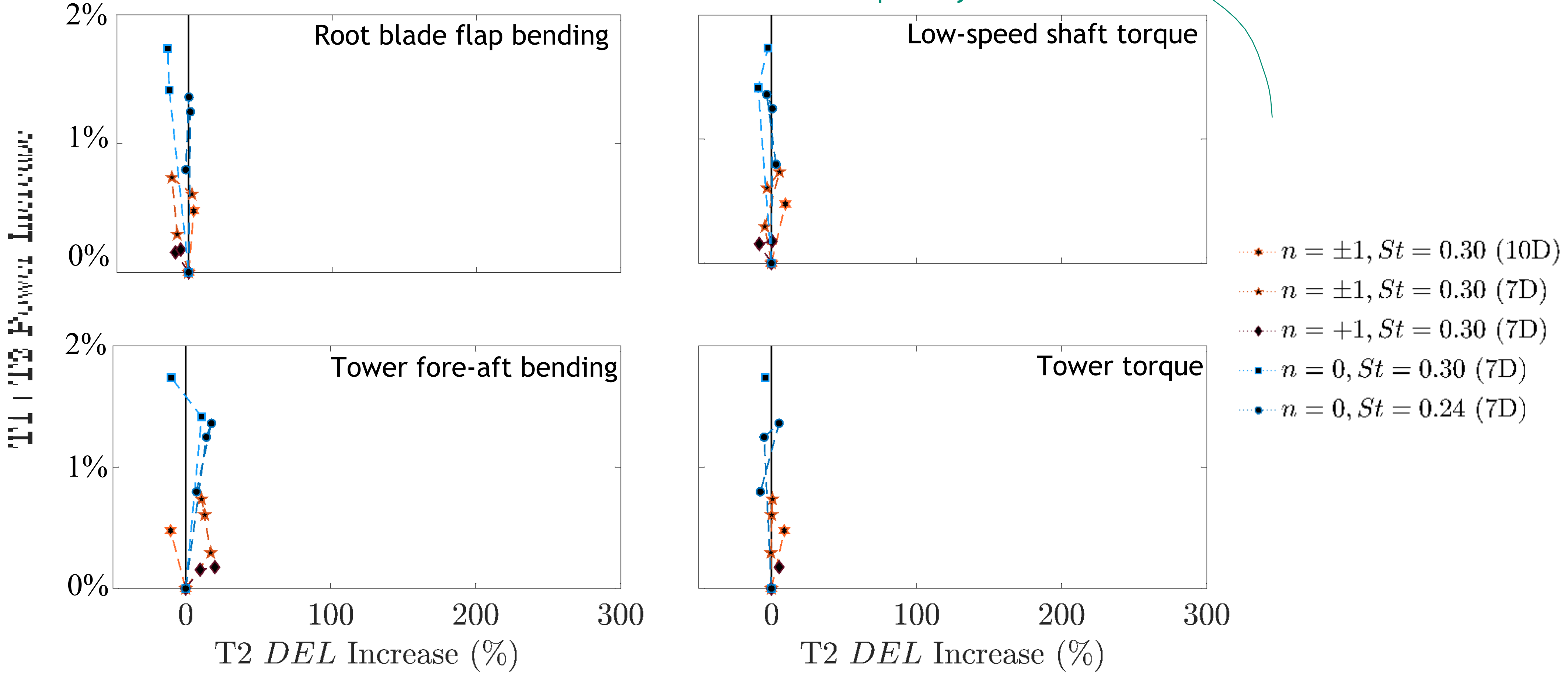


Impact to upstream turbine DEL differs depending on turbine component and forcing strategy

Results for turbulent inflow

Turbine reliability (downstream turbine fatigue)

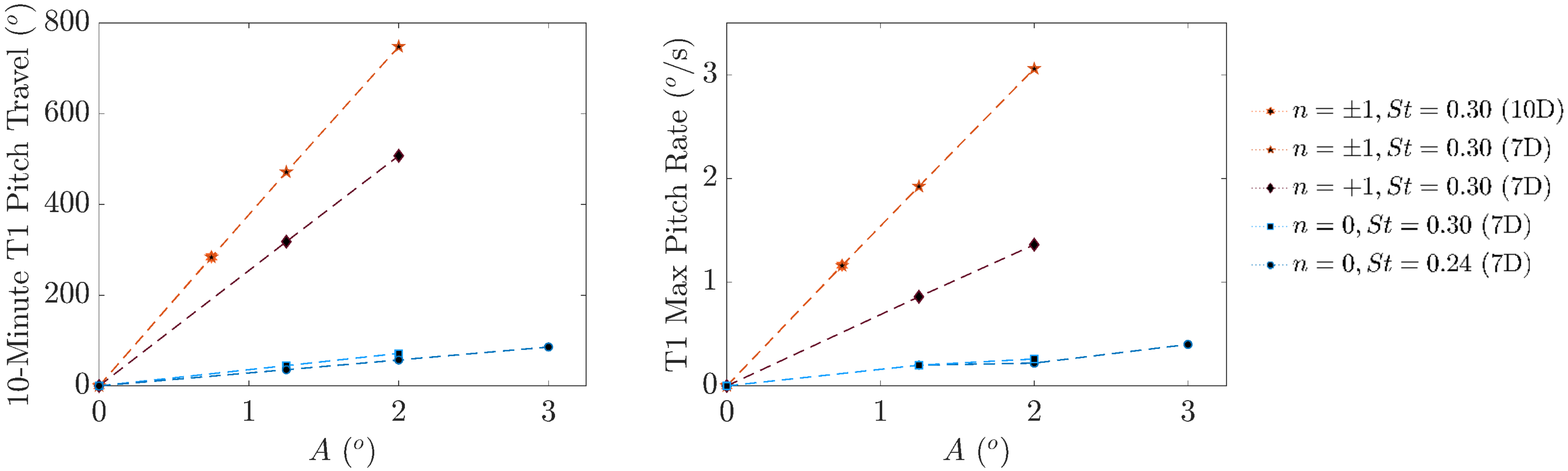
Higher benefit-to-penalty ratio



Impacts to downstream turbine DELs are minor

Results for turbulent inflow

Turbine reliability (active turbine pitch bearing/actuator wear)



The pitch wear increases with AWC are smaller for the $n = 0$ cases

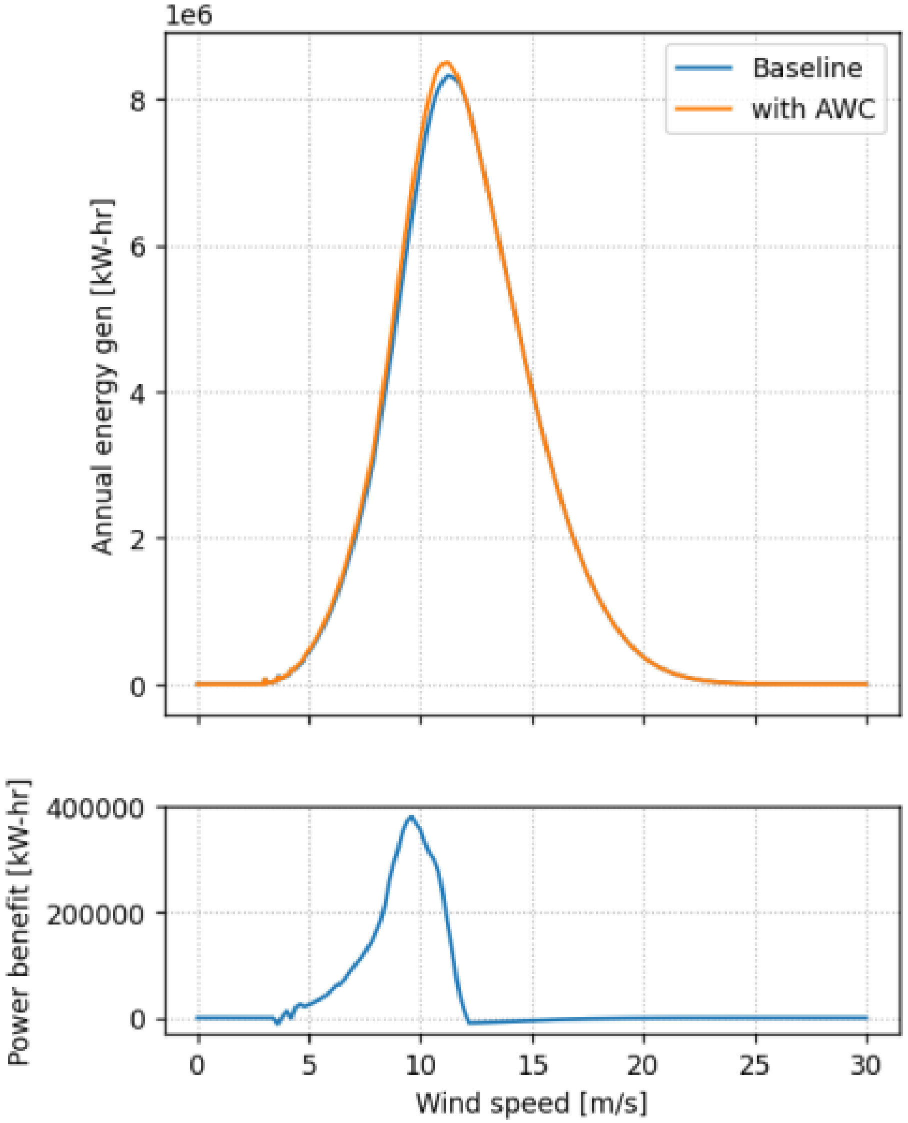
Estimated total AEP benefits

<u>Turbine parameters</u>
Farm: 4 turbine row with 7D spacing
Model: GE 2.8-127
Rated power: 2.8 MW
Rotor diameter: 127m

<u>Wind distribution</u>
Scale factor: 11 m/s
Shape factor: 2.773

<u>AWC assumptions</u>
- Conditions allow AWC to be applied 34% of time
- 0.5% penalty on T1
- 6% benefit on T2, 3% on T3, 1.5% on T4

<u>Power benefit</u>
- Most benefit from AWC comes from below rated wind speeds
- **Total AEP benefit approximately 2%**



Conclusions and summary

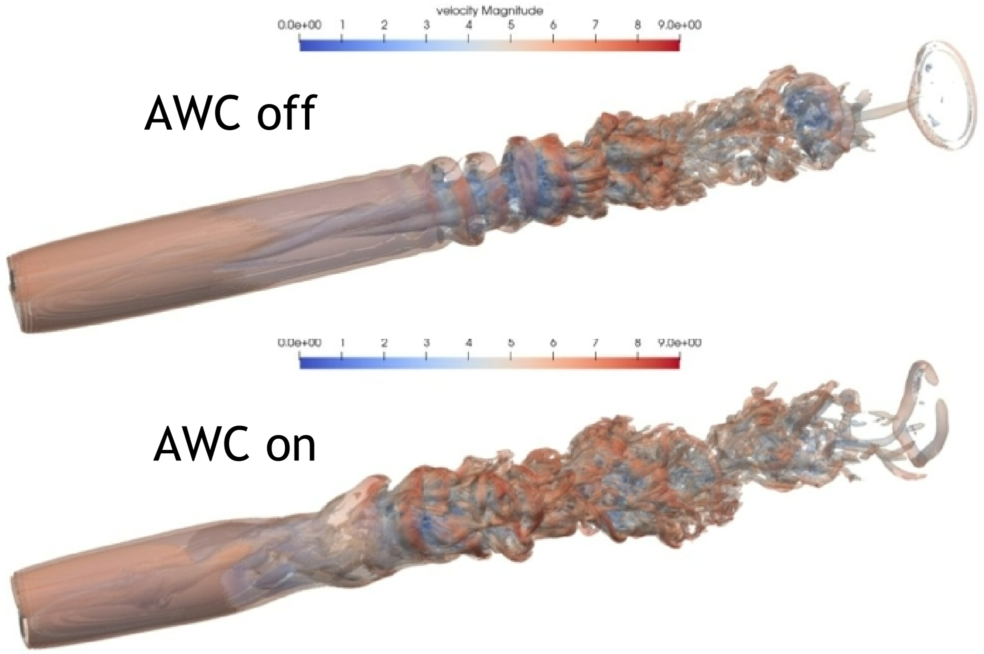
Linear stability theory offers means to predict optimal forcing strategies for AWC

An example turbulent inflow was created to match measured stable atmospheric conditions at a DOE SGP measurement site

Initial trials of AWC indicate that two-turbine power increases of 1.5-2.0% are likely possible with this inflow; additional gains are expected for third and fourth turbines

Changes in the upstream turbine’s fatigue and pitch wear can be significant if forcing amplitude is too large

Most benefit from AWC comes from below rated wind speeds; total AEP benefit may be on the order of 2%



Demonstration of AWC on 2.8MW 127m turbine