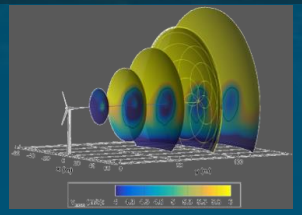
SAND2022-14687 PE

Improving Wind Farm Power Output with Active Wake Mixing



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PRESENTED BY

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Sandia Blade Workshop 2022

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Outline

Overview of wake control methods

How does AWM work?

Use of linear stability theory in active wake mixing

Demonstration of wake control authority on canonical inflow example

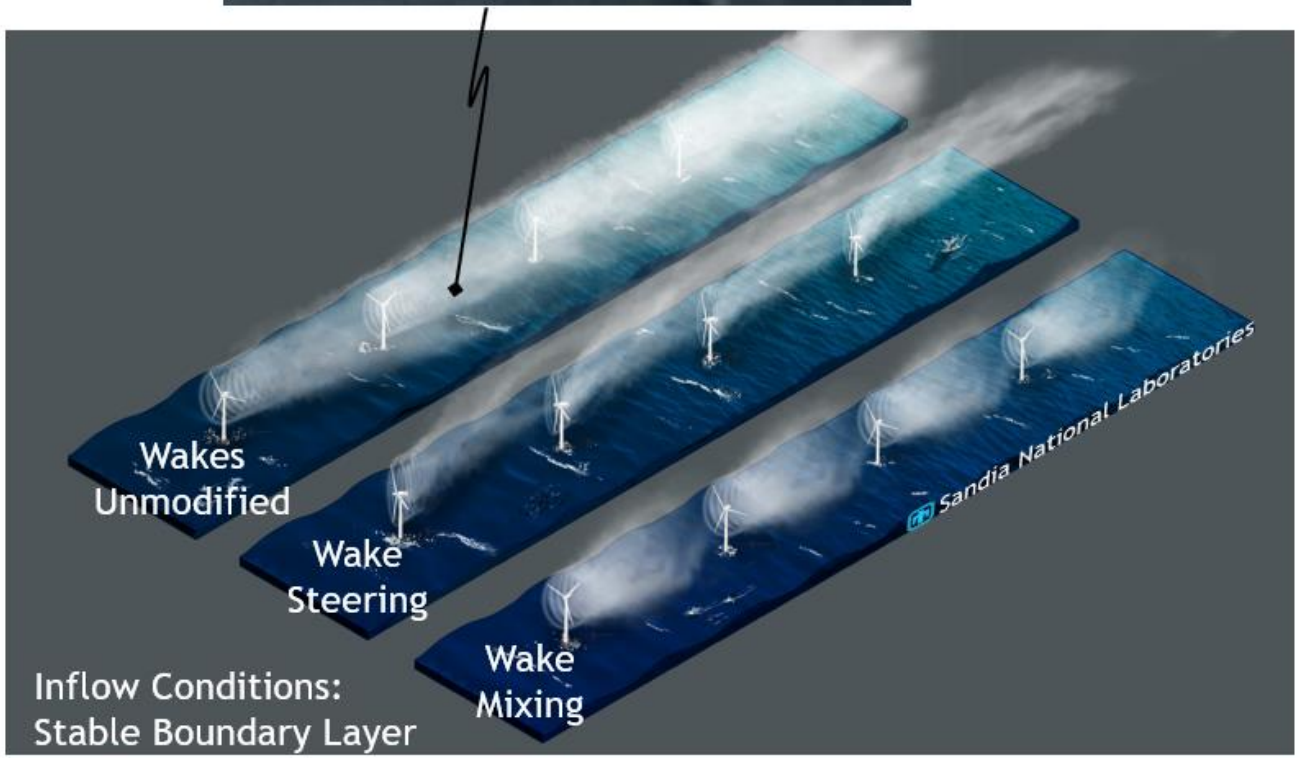
Demonstration of wake control authority on realistic inflow example

AEP estimates

Conclusions/Future Work

Horns Rev 2 Offshore Wind Plant

Downstream turbines engulfed in wake shadow produce less power



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- Why wake control?
- Pros/cons of different wake control strategies

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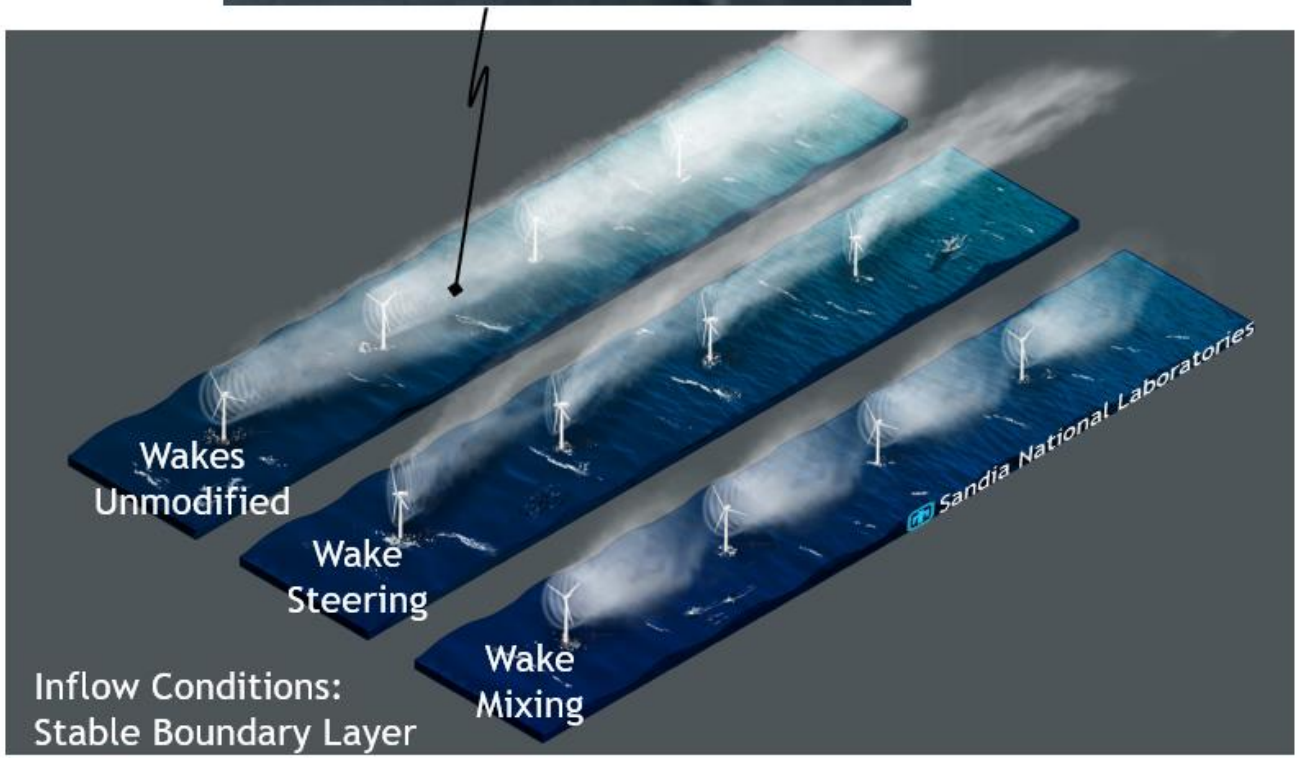
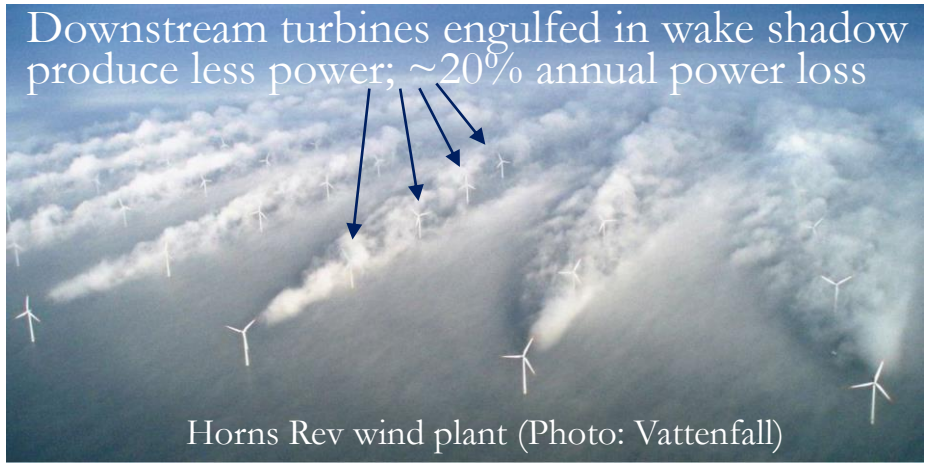


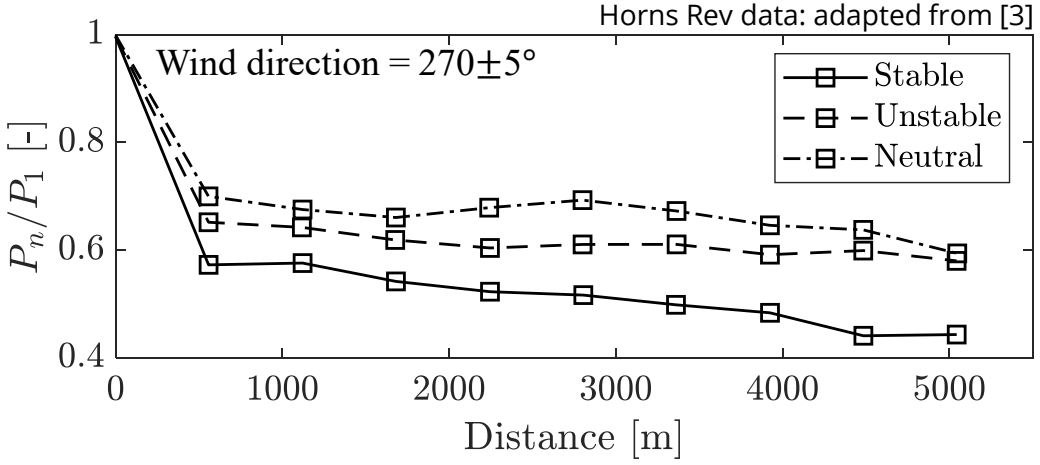
Why Wake Control?

Conflicting needs in siting of wind plants:

- We want **small plant footprints** to
  - Reduce cable-laying installation and maintenance costs
  - Accommodate zoning
    - Environmental requirements
    - Shipping lanes (offshore)
    - Setbacks
- But we need **wide spacing** to
  - Mitigate power losses due to wakes, especially in offshore stable atmospheres
    - Deep array power losses have been observed larger than 40% for aligned turbines in stable atmospheric boundary layers (ABLs) [1,2].
  - Reduce fatigue loads due to wake effects

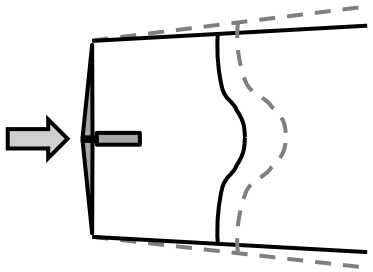


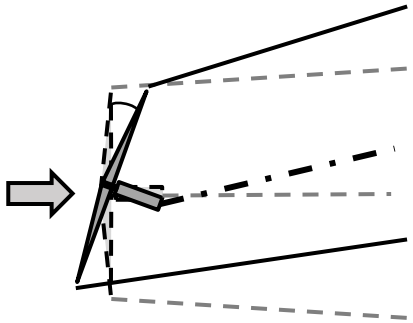
Horns Rev data: adapted from [3]

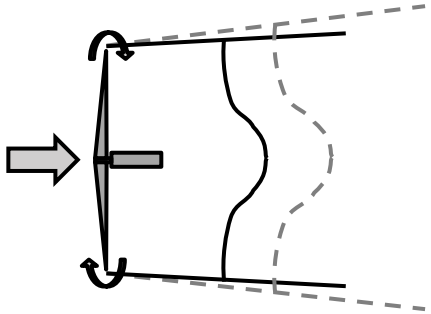


As offshore turbine diameters increase, the spacing problem worsens.

Pros/Cons of Existing Wake Control Techniques





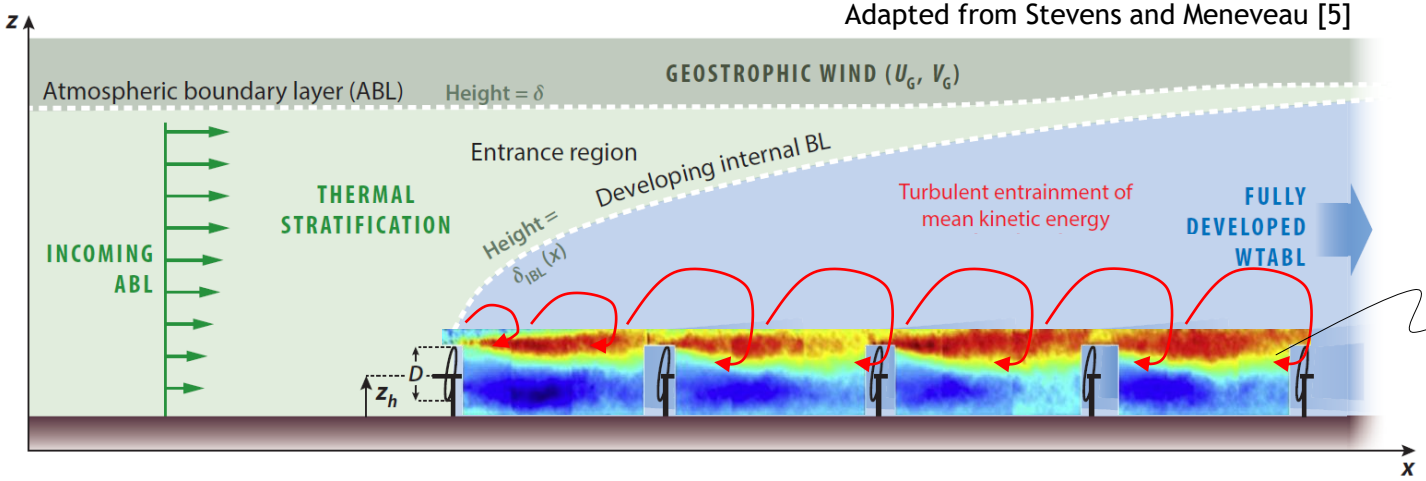


	Operating Principle	Pros	Cons	Commercial Packages
Derating	Deficit Management	Small AEP increases possible Small load reductions possible	Large power loss in controlled turbine(s) Actuation required in most turbines High uncertainty in achieving benefits Typically open-loop control	Wind sector management packages sometimes integrate derating
Wake Steering	Deficit Management	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	Siemens-Gamesa Wake Adapt (≤1% AEP gain), others?
Wake Mixing	Deficit Reenergizing	Well-suited for closed-loop control with active sensing input Limited subset of turbines require actuation In deep array scenarios, power gains likely relatively insensitive to turbine-wind alignment	Load increases on actuated turbine(s) Increased actuator wear (if active pitch control used)	N/A

Primary source: Houck [4]

Pros/Cons of Existing Wake Control Techniques

Adapted from Stevens and Meneveau [5]



Isocontours of turbulent MKE entrainment from Newman et al. [6] show that, once the boundary layer develops, entrainment from above is fairly constant moving down the turbine column

Re-energizing of flow in deep arrays comes from aloft, but the entrainment from above can only be as large as turbulent mixing allows (see also the analogous canopy flow)

Wake steering/derating are deficit *management* techniques; no matter how much steering/derating is done, you are not affecting the vertical entrainment of MKE to the first order

AWM is fundamentally different than wake steering/derating because it intentionally *re-energizes* the deficit

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How does AWM work?

- Targeting inherent wake instabilities
- Available control vectors

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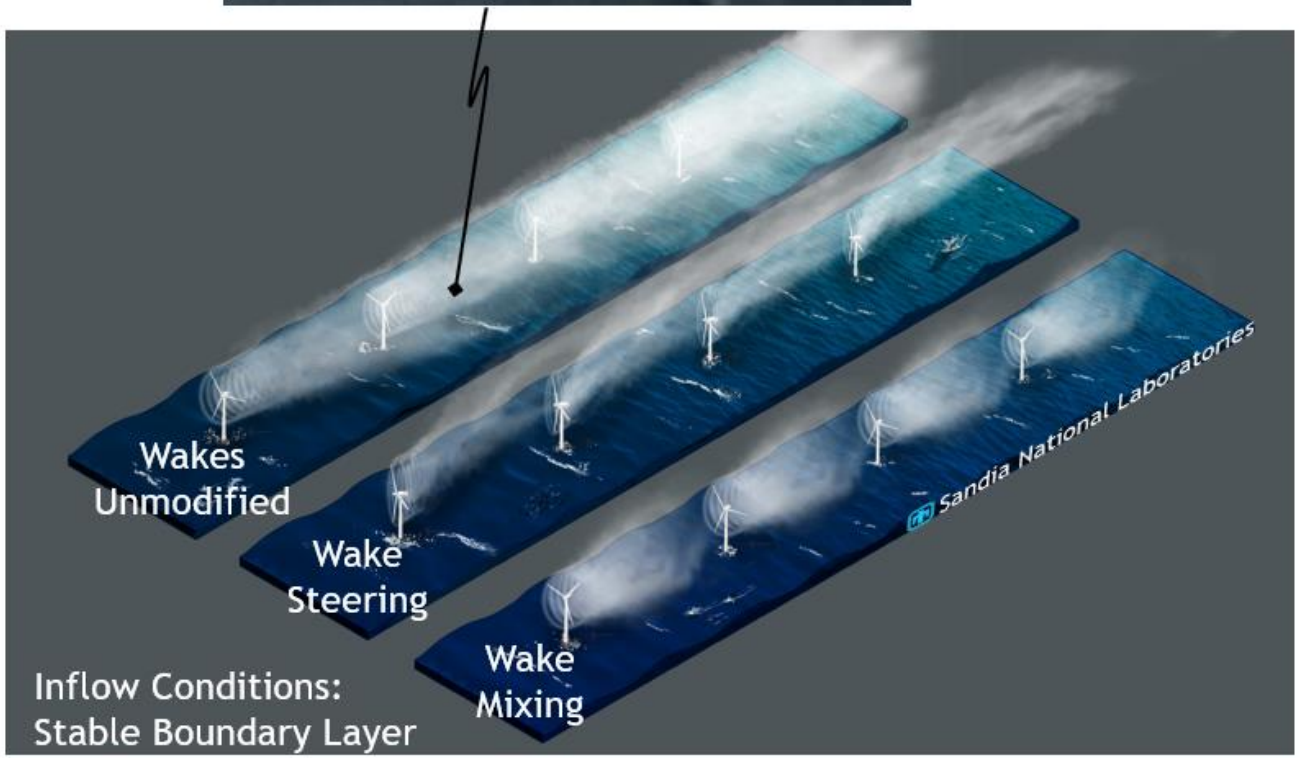


Targeting Inherent Wake Instabilities

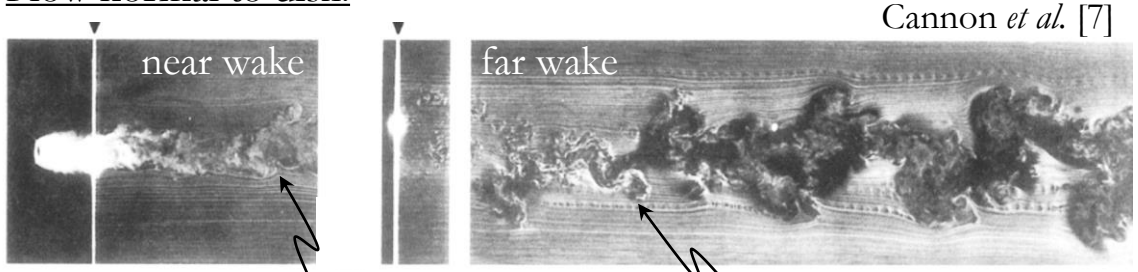
Inherent wake instabilities

- Hub vortex – frequency scaling not unanimously agreed
- Tip vortex – frequency scaling on RPM
- Bluff body – frequency scaling on U_∞/D

Bluff-body instabilities:

Flow normal to disk:

Cannon *et al.* [7]



Initial perturbations

Coherent structures with $St_D \approx 0.15$ help to entrain ambient fluid

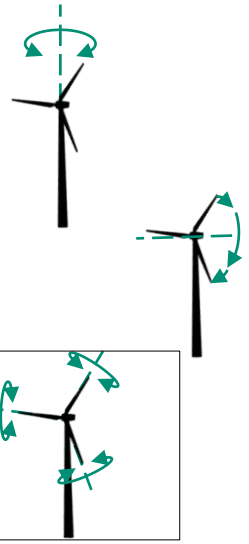
Flow normal to wind turbine:

- "[There is] vortex shedding from the turbine disc, much in the same way as one would expect for a solid disc." -Medici and Alfredsson [8]
- Recent authors have found preferred excitation frequencies found in the St_D range of 0.2-0.5 [9-14]
  - Preferred frequencies are lower than those of the tip vortex instability (roughly an order of magnitude lower for the configuration of this study)

Exciting bluff body instabilities is another approach to improving wake recovery

Control vectors for Active Wake Mixing (AWM)

What are possible control vectors for implementing wake control?



Periodic yawing: typical yaw rates of large turbines (0.3°/s for the NREL 5MW [15]) 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:

$$\underbrace{\beta}_{\text{dynamic pitch setting}} = \underbrace{\beta_0}_{\text{conventional pitch set point}} + \sum \overbrace{A}^{\text{amplitude}} \sin(2\pi \underbrace{St_D}_{\text{Strouhal number}} U_{hub} D^{-1} t + \underbrace{n}_{\text{azimuthal mode number}}\theta + \overbrace{\phi}^{\text{phase}})$$

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 strategy

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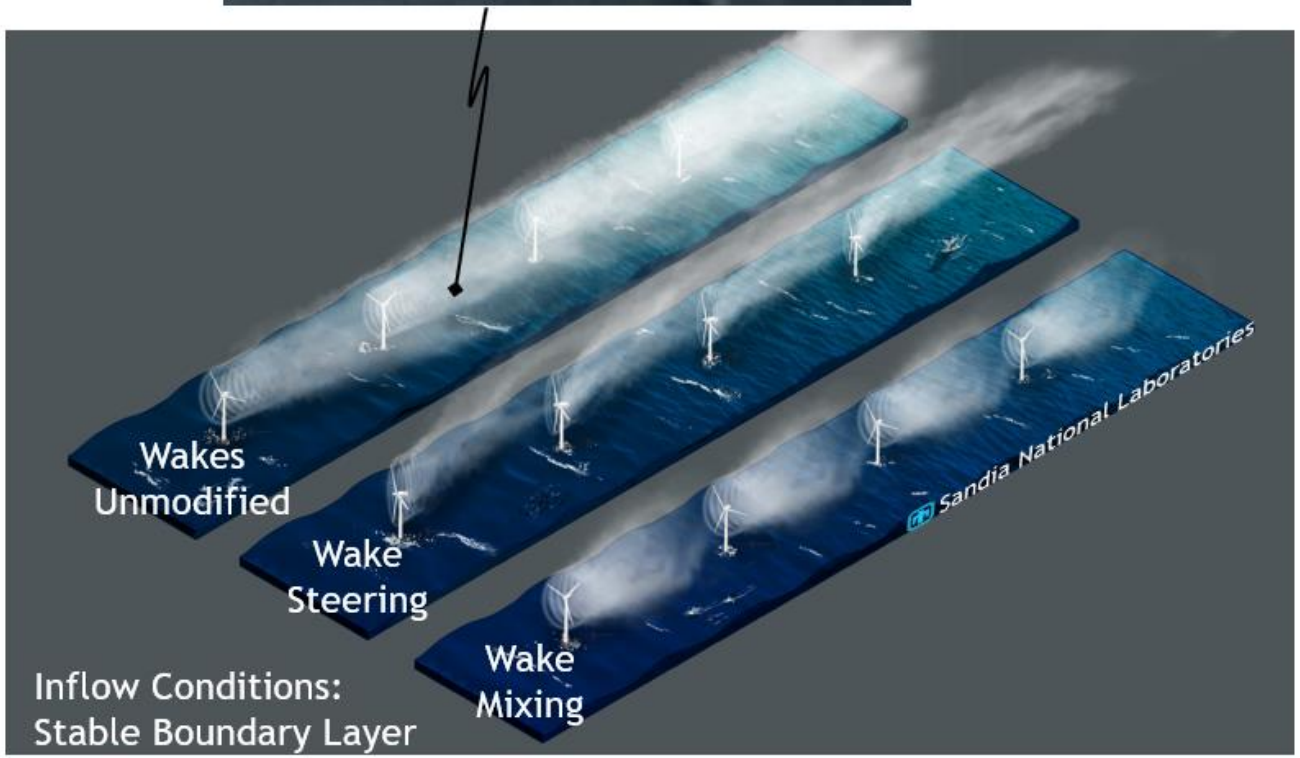


Using Linear Stability Analysis to Model Large Scale Structures in Wakes

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

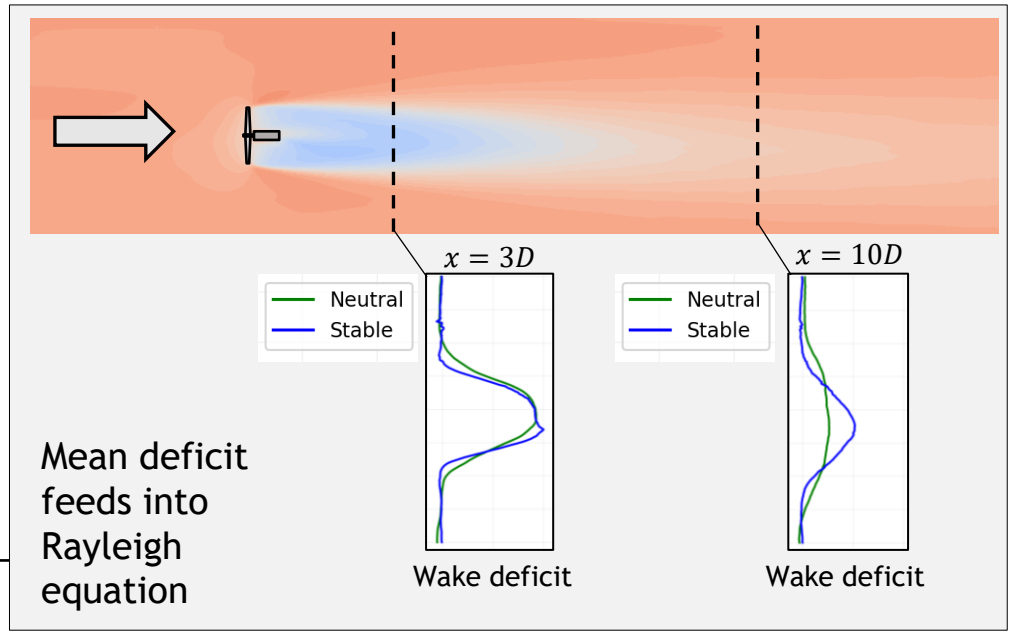
- Flow quantities are decomposed in terms of mean and fluctuating components

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

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

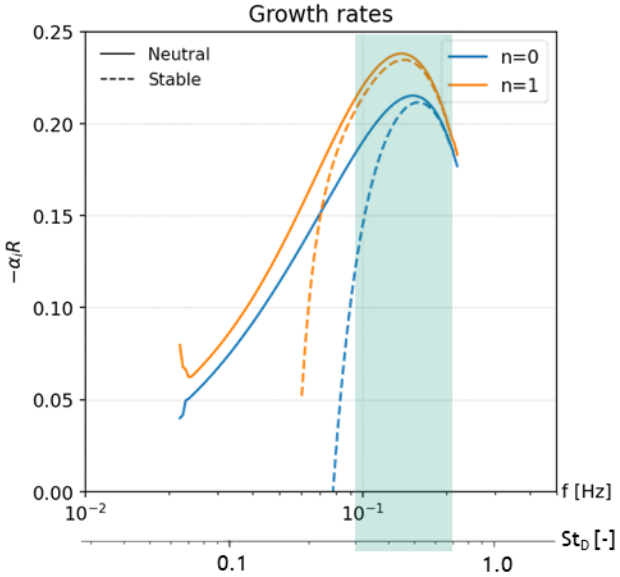
- For inviscid parallel flow, problem collapses to Rayleigh equation (Batchelor & Gill [16] ; Drazin & Reid [17]):

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



Use spatial stability analysis: disturbances grow downstream

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



Results of buoyancy-informed 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

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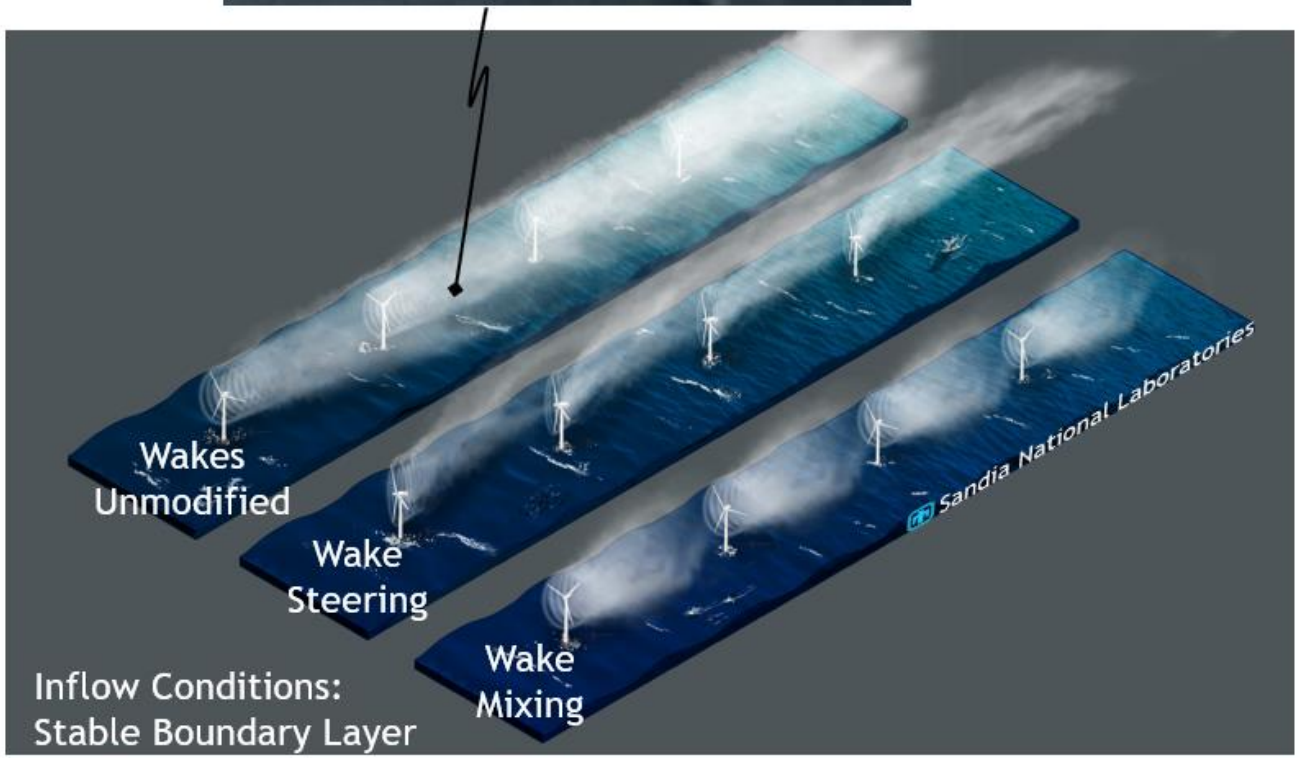
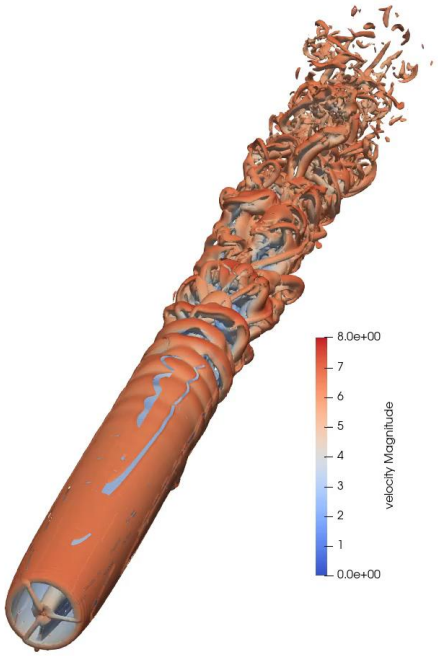


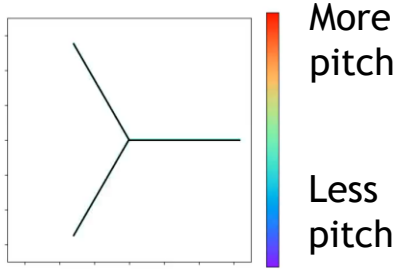
Canonical Inflow Examples

Visualization of large-scale structures

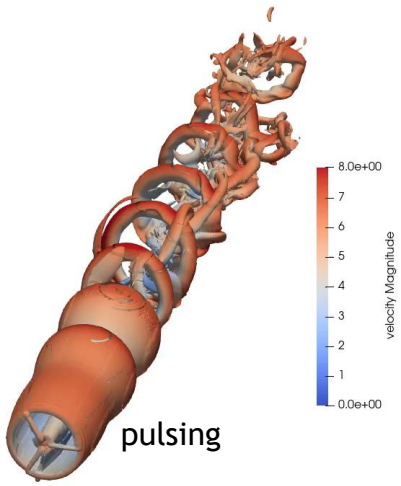
Example of AWM using IPC
- Force at St=0.30 with varying n
- Steady uniform inflow at 6.4 m/s, free space
- AWM through IPC excites large scale structures earlier

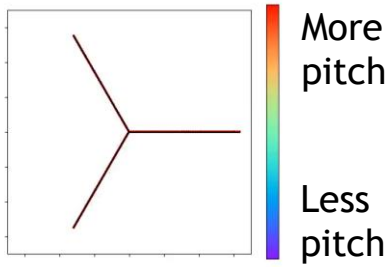
No wake control



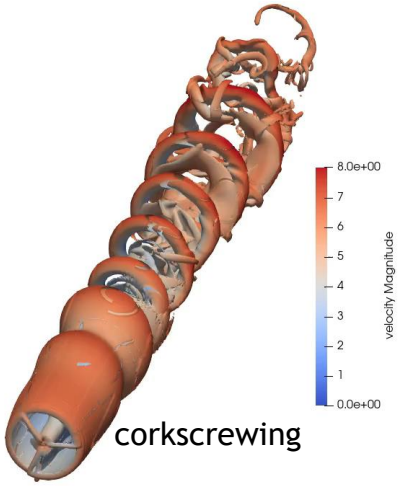


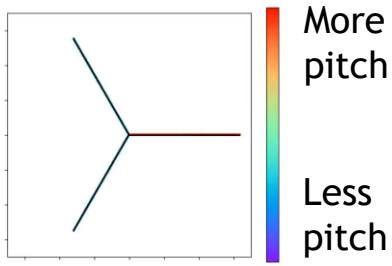
$n = 0$
(a.k.a., collective dynamic induction control)



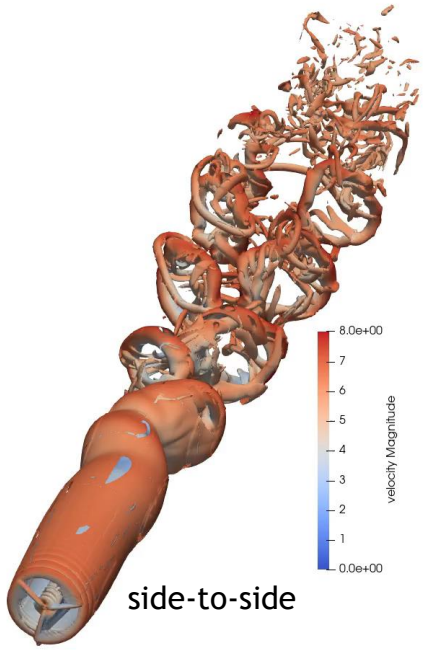


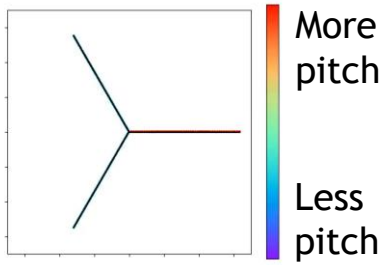
$n = +1$
(a.k.a., helix control [18])





$n = \pm 1$

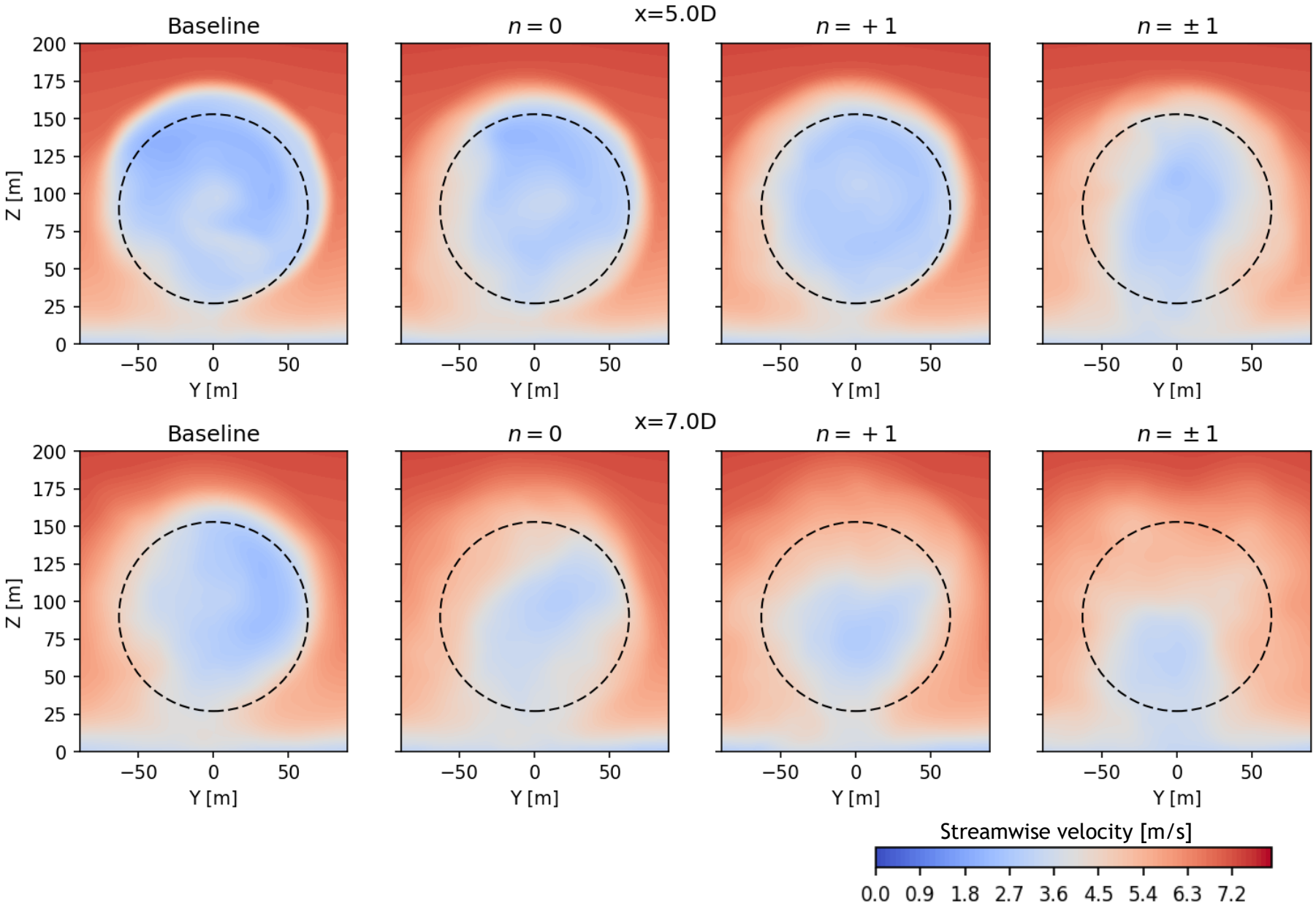




Time averaged wake planes

AWM using IPC

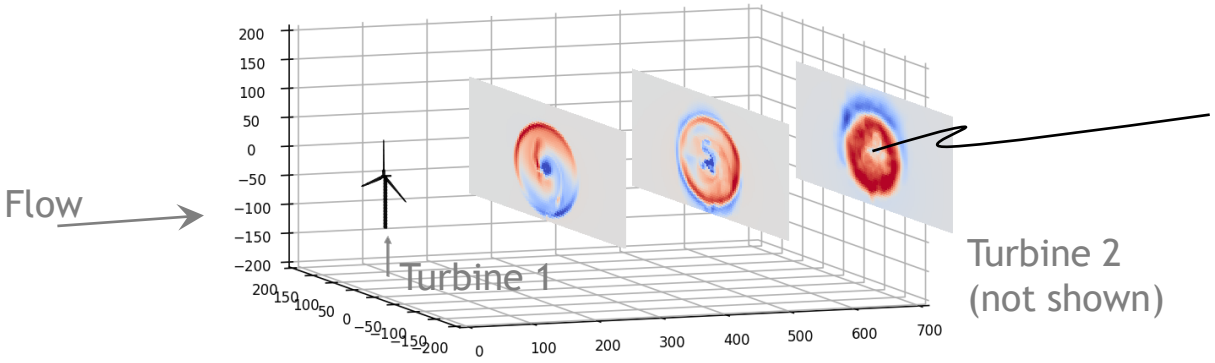
- Force at St=0.30 with varying n and blade pitch amplitude
- Neutral inflow at 6.4 m/s and shear α = 0.17, with ground effect
- No turbulence



Canonical Inflow Examples

Effect on wake velocity → Specific example case: $n = \pm 1$

Delta: modified minus unmodified wake



The evolving red region indicates the added kinetic energy available to Turbine 2 due to active wake mixing

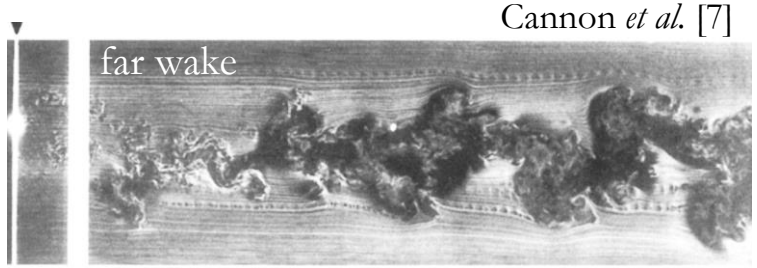
Cf., Canonical Bluff Body Shedding

Inherent wake instabilities

- Hub vortex – frequency scaling not unanimously agreed
- Tip vortex – frequency scaling on RPM
- Bluff body – frequency scaling on U_∞/D

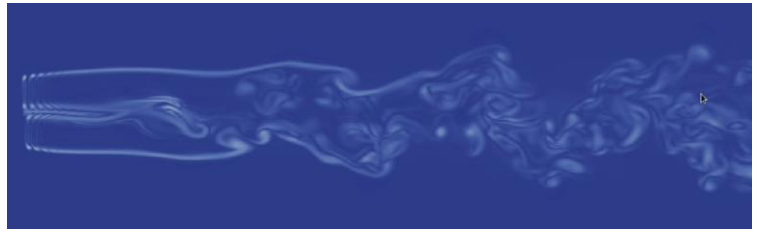
Flow normal to disk:

Cannon *et al.* [7]



Flow normal to rotor:
(with excited modes)

LES wind turbine wake with AWM



Reiterate: Active wake mixing can amplify the same type of fluid structures known from canonical bluff-body shedding

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Demonstration of wake control authority on realistic inflow example

- Large eddy simulation methodology
- Generating a realistic turbulent inflow
- Baseline wake analysis
- Actuated wake analysis
- Power benefit vs. reliability penalty

AEP estimates

Conclusions/Future Work

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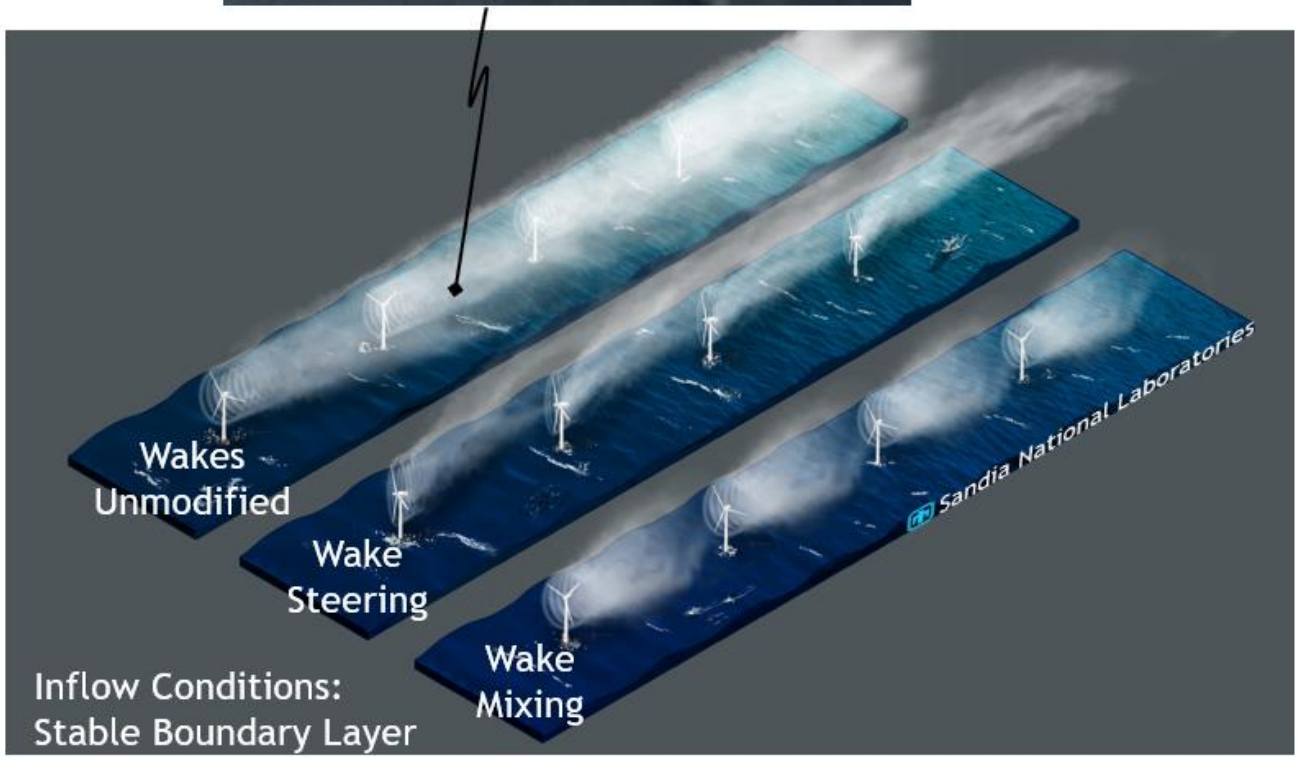


Large Eddy Simulation Methodology

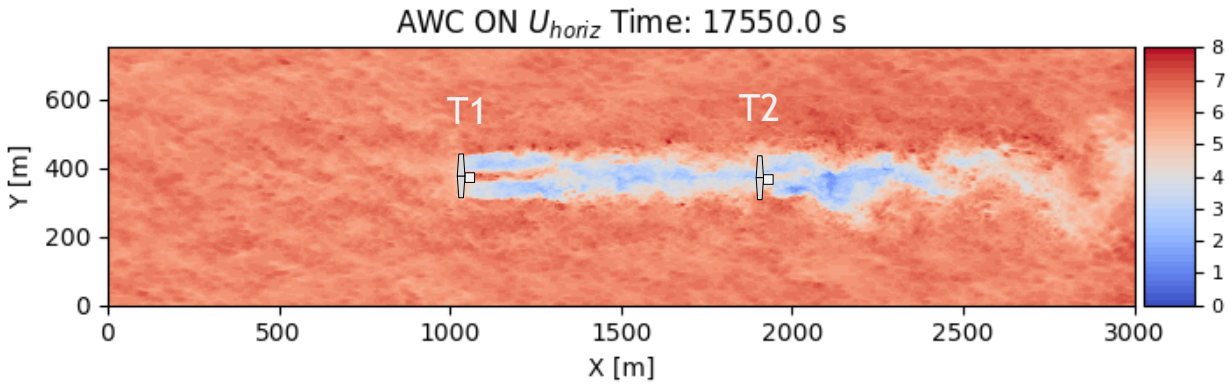
ExaWind/Nalu-Wind[1] Solver:

- 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 [19] and Monin-Obukhov similarity theory

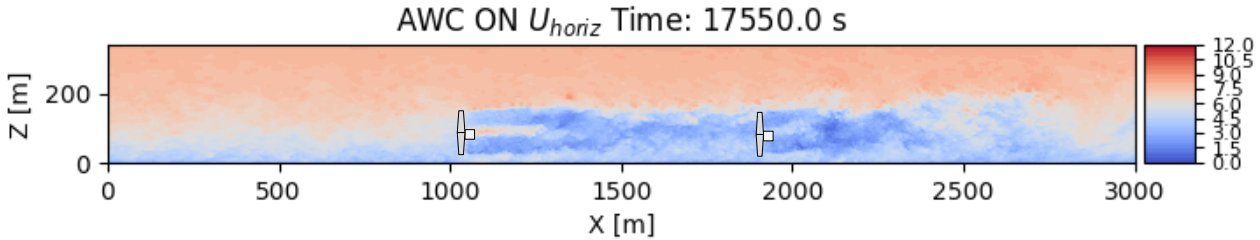
Turbine model & controller

- 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
- AWM with pitch control implemented in ROSCO

Hub-height plane: horizontal velocity



Streamwise plane: horizontal velocity



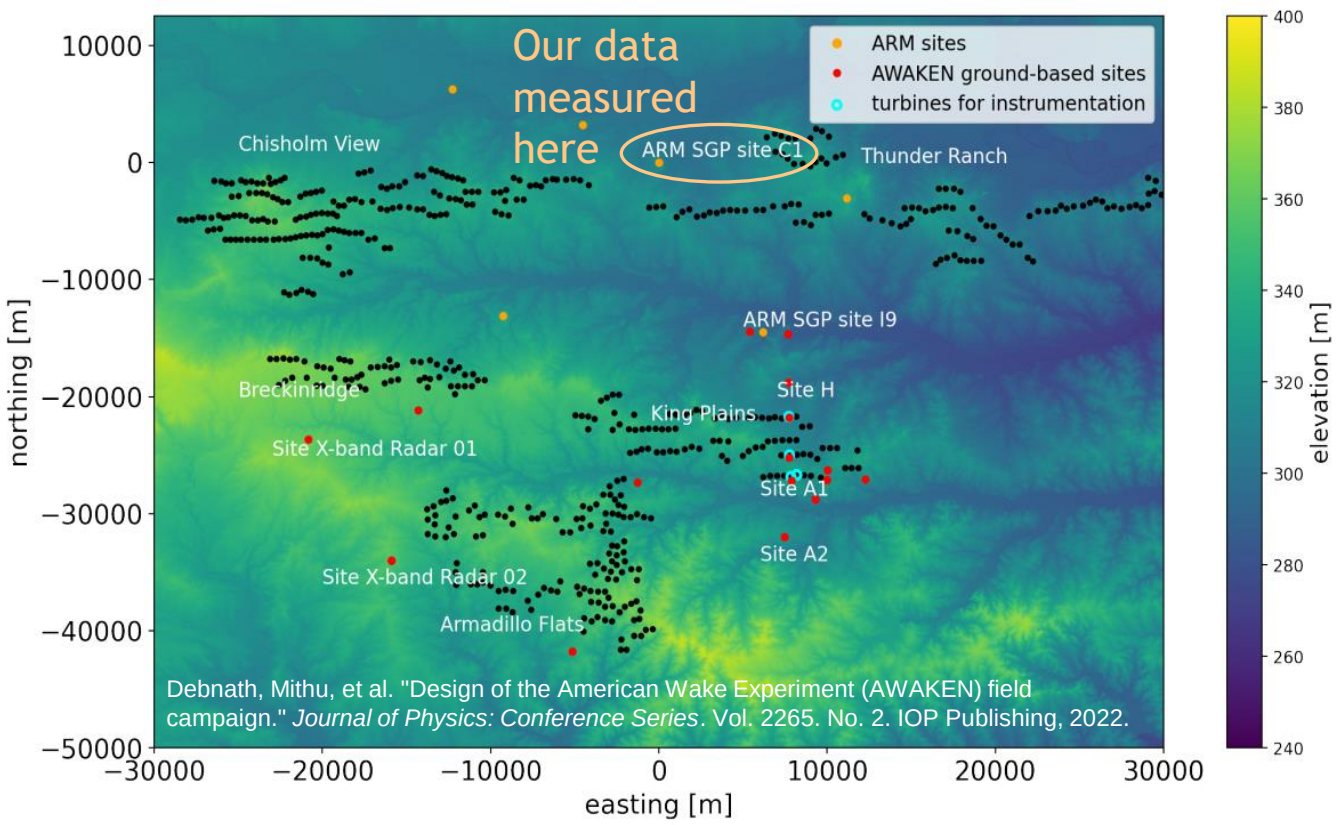
Mesh: 64M elements
Domain: 3km x 0.75km x 1km
Averaging time: 14 minutes (after transient runout)

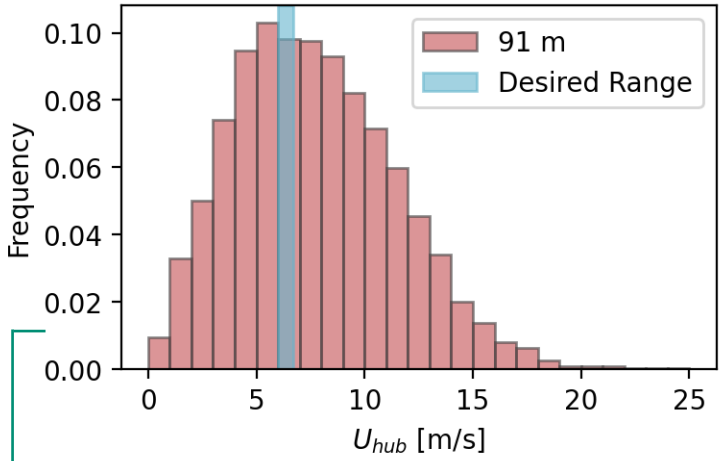
[1] http://github.com/Exawind/nalu-wind

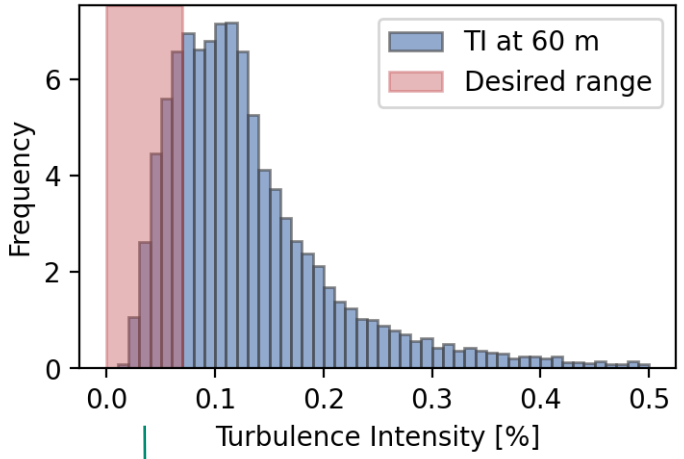
Generating a Realistic Turbulent Inflow

Developing a stable, Region II inflow condition to demonstrate AWM

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



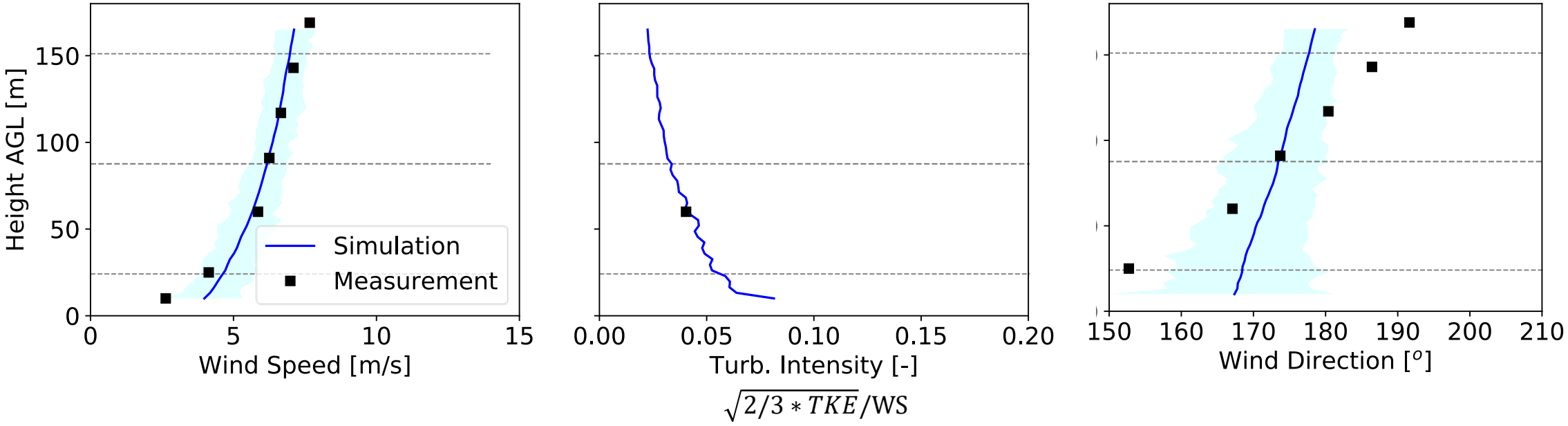




- Filters applied: wind speed (6-6.7 m/s), turb. intensity (0-7%),
- wind direction (100-260°), veer (>20°)
- 230 minutes of data meet the criteria and were used to generate the background flow

Generating a Realistic Turbulent Inflow

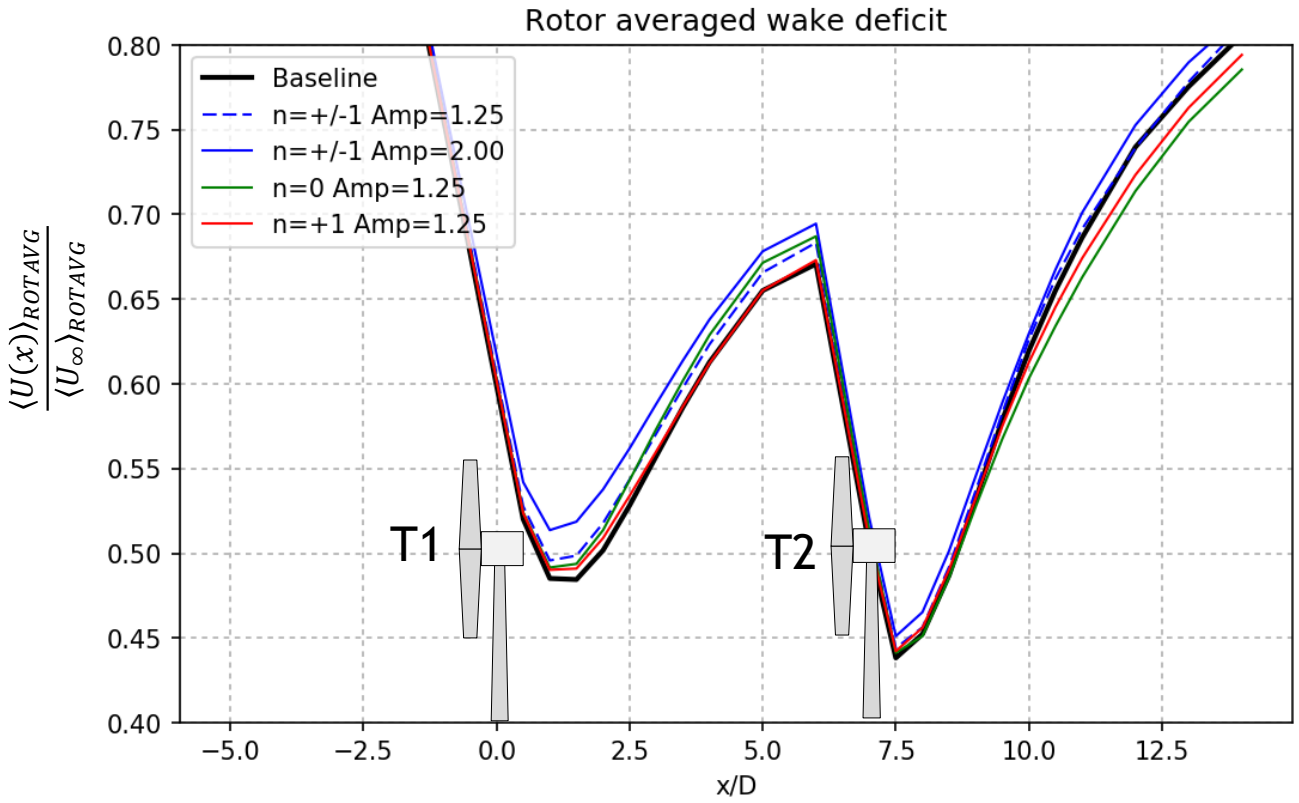
Achieved vs. target inflow conditions

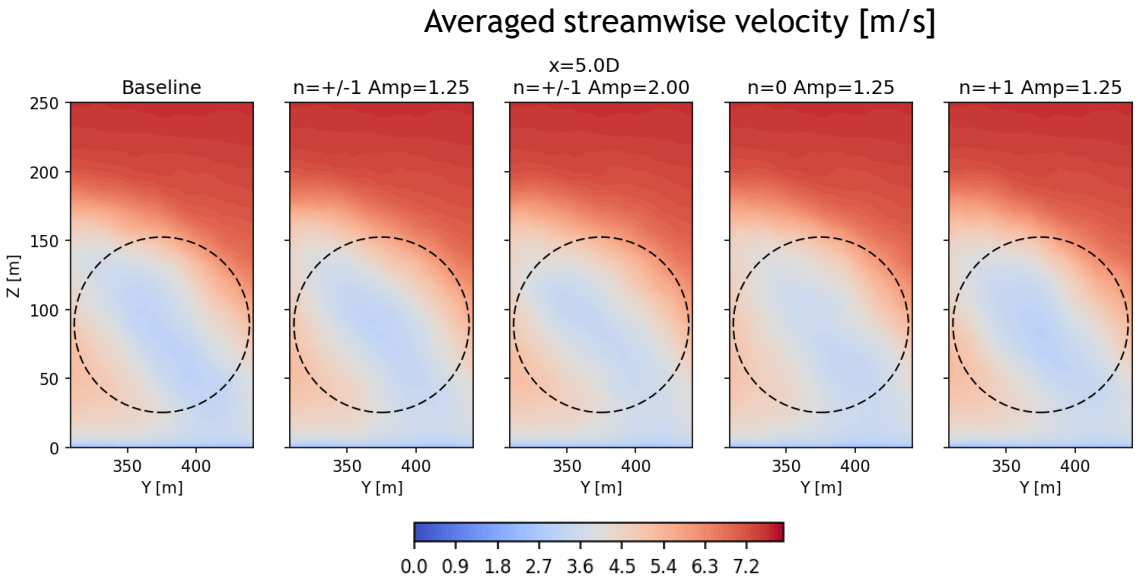


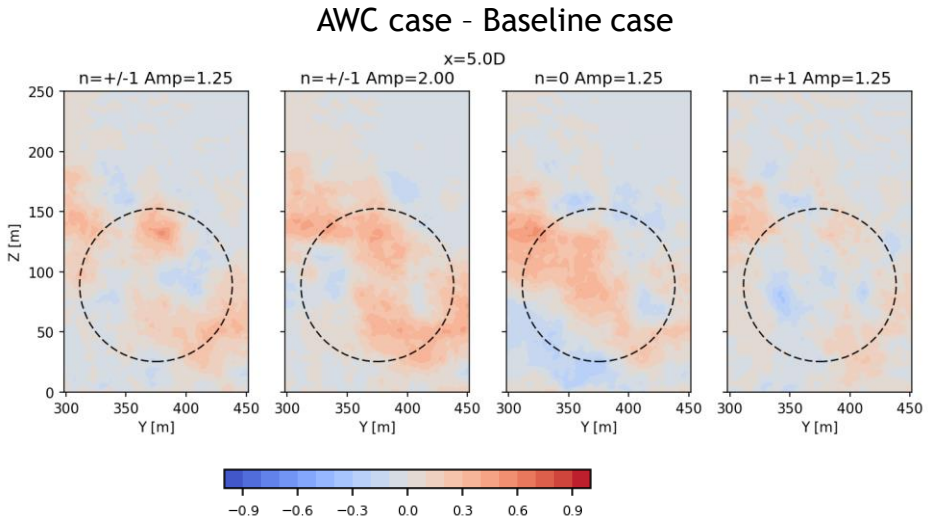
Simulated shear and turbulence match the measurement well

Actuated Wake Analysis

Rotor-averaged wind deficit comparison





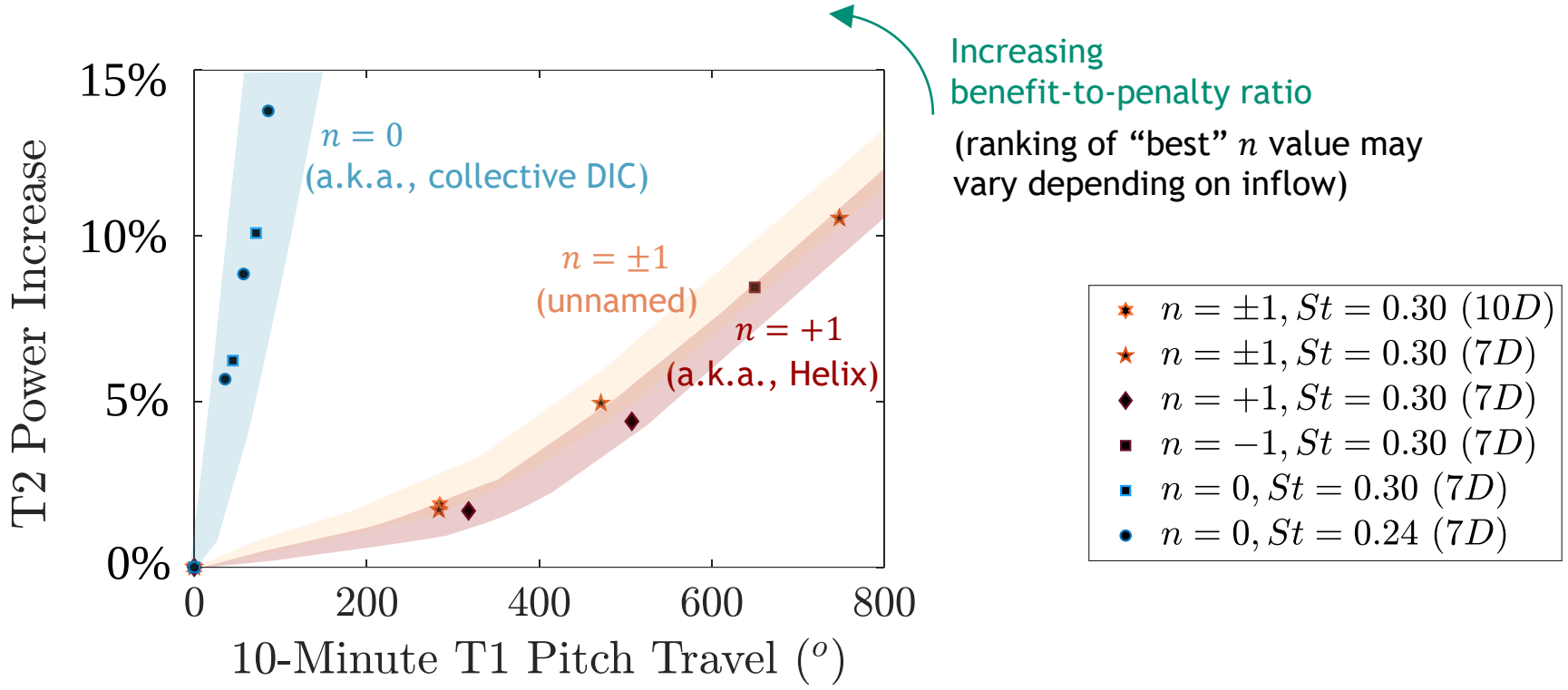


- $n = 0$ and $n = \pm 1$ AWC forcing on T1 show positive wake benefit downstream
- Residual wake benefits observed downstream of T2 for $n = \pm 1$ forcing

Power Benefit vs. Reliability Penalty

Preliminary results

Pitch travel taken as surrogate for turbine reliability penalty here because pitching (1) increases pitch bearing wear and (2) creates blade fatigue



Aligned, downstream turbines could see 2-15% increase in power; power penalty for upstream turbine ~0.5-5%.

Outline

Overview of wake control methods

How does AWM work?

Use of linear stability theory in active wake mixing

Demonstration of wake control authority on canonical inflow example

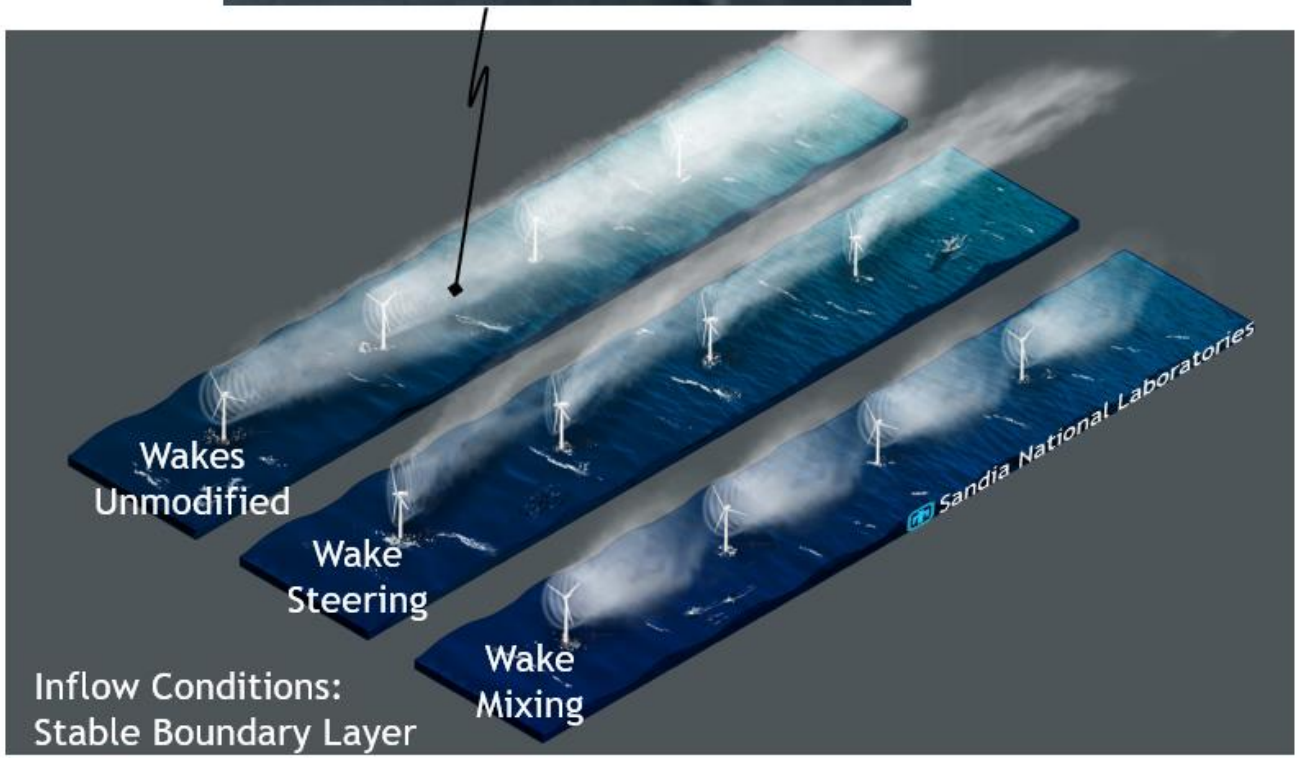
Demonstration of wake control authority on realistic inflow example

AEP estimates

Conclusions/Future Work

Horns Rev 2 Offshore Wind Plant

Downstream turbines engulfed in wake shadow produce less power



Estimated total AEP benefits

Turbine parameters

Farm: 4 turbine row with 7D spacing

Model: GE 2.8-127

Rated power: 2.8 MW

Rotor diameter: 127m

Wind distribution

Scale factor: 11 m/s

Shape factor: 2.773

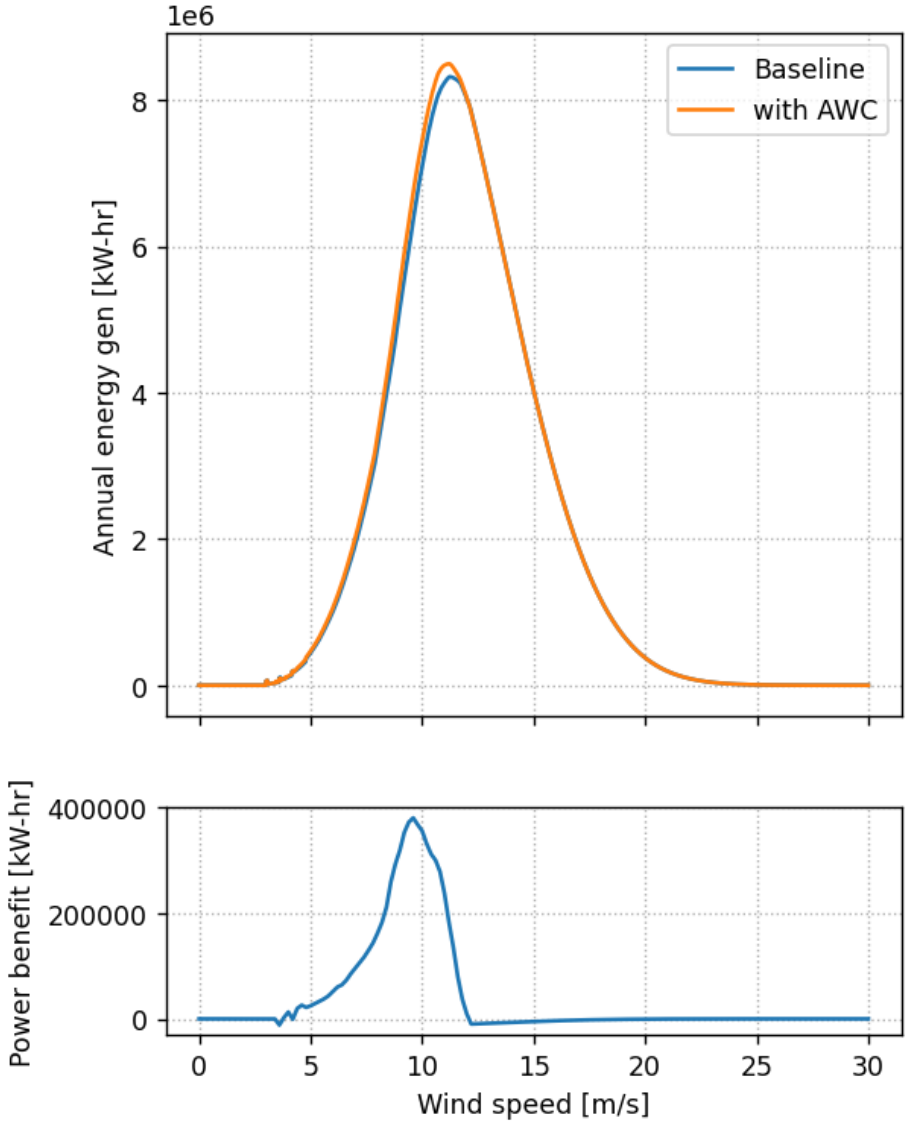
AWM assumptions

- Conditions allow AWM to be applied 34% of time
- 0.5% penalty on T1
- 6% benefit on T2, 3% on T3, 1.5% on T4

  (simplifying assumption: benefit is constant with wind direction)

Power benefit

- Most benefit from AWM comes from below rated wind speeds
- **Total AEP benefit approximately 2%**



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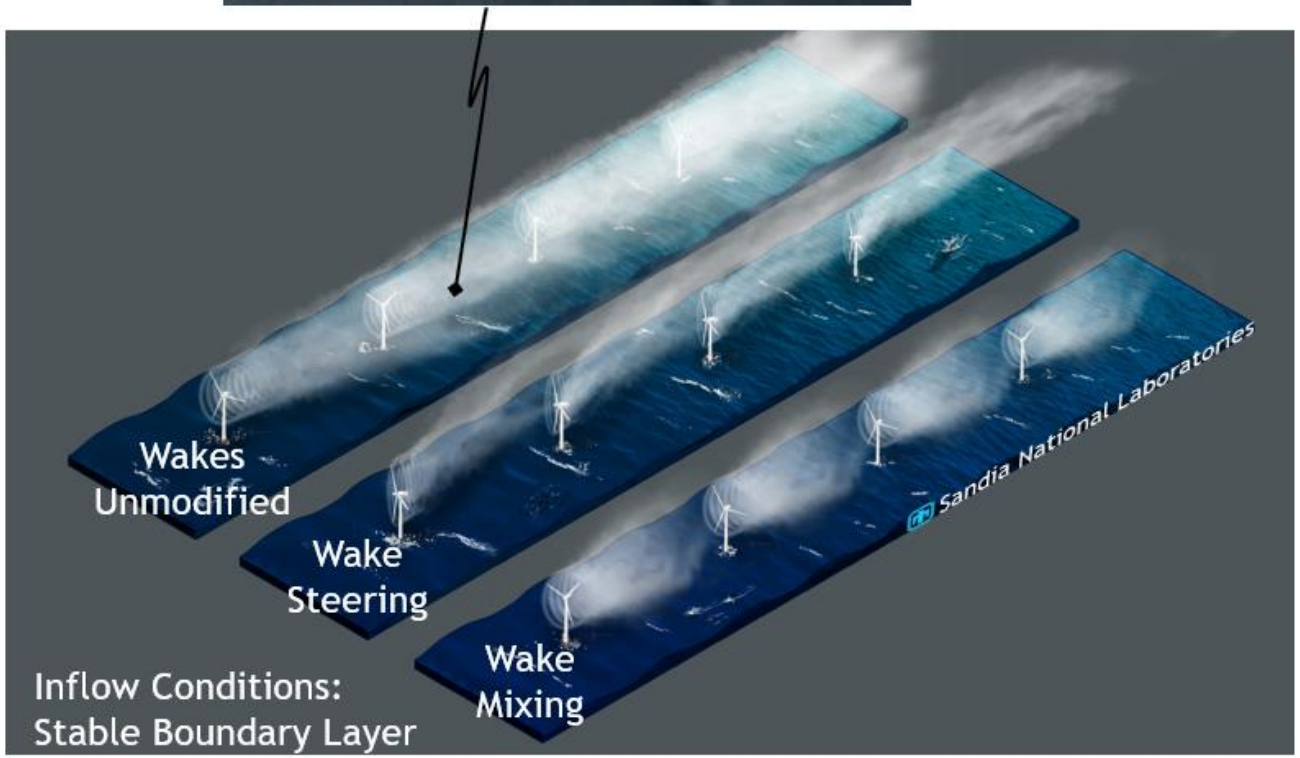


Conclusions and Summary

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

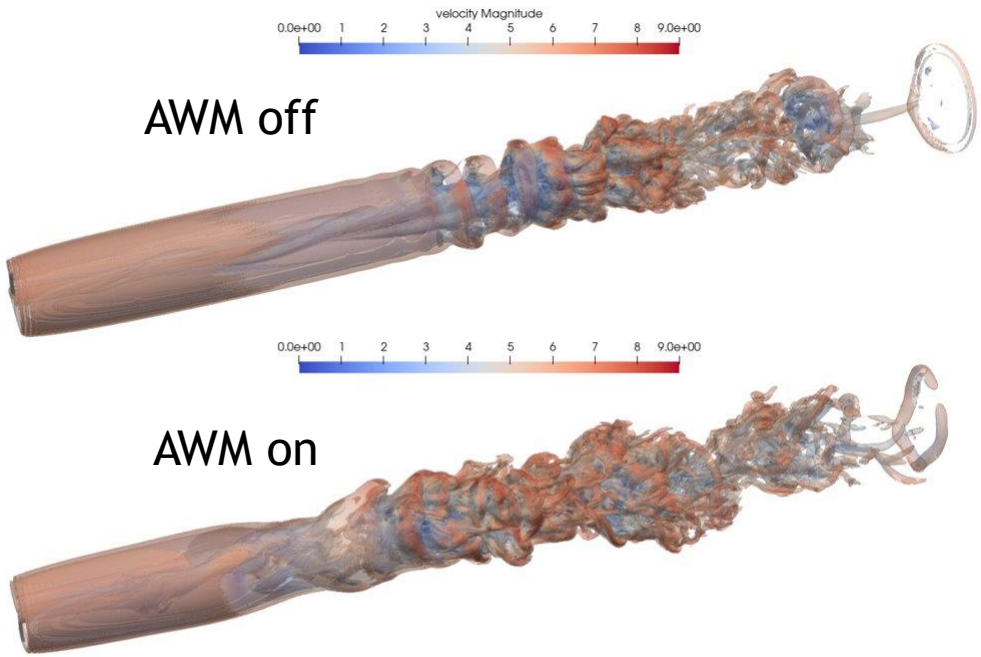
An example turbulent inflow was created to match measured stable atmospheric conditions at a DOE SGP measurement site

Initial trials of AWM indicate that second-turbine power increases of 10% are likely possible with this inflow; additional gains are expected for third and fourth turbines

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

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

Work in 2023 funded by the DOE Wind Energy Technologies Office will demonstrate control authority and cost/benefit on larger turbine array



Demonstration of AWM on 2.8MW 127m turbine

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