Capturing Time-Varying Wake Dynamics Using Hybridized Actuator Disks in Steady-State Simulations for Improved Optimization Efficiency

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Jeffery M. Allen[a], Ethan Young[a], Pietro Bortolotti[b],
Garrett Barter[b]

[a]Computational Science Center, NREL
[b]National Wind Technology Center, NREL

Outline

1 The Software Package

2 ALM-2-Disk

3 Flexibility and Robustness

4 Yaw Optimization

5 Conclusions and Future

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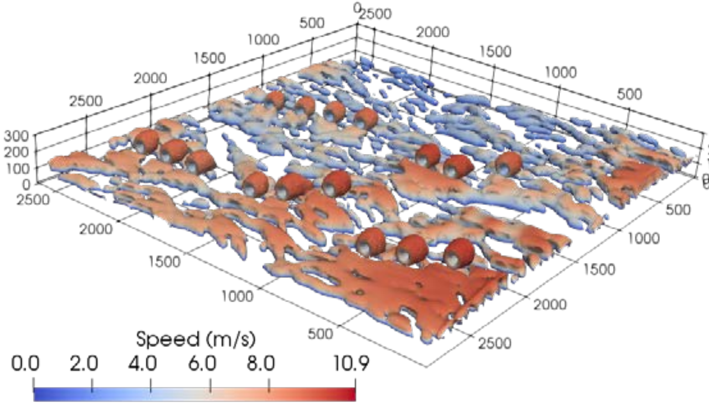
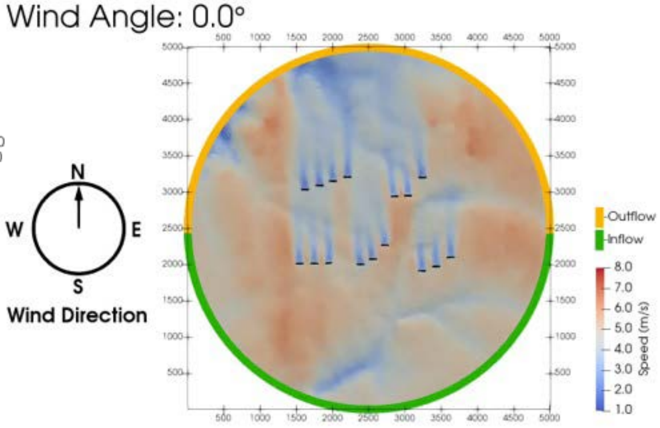
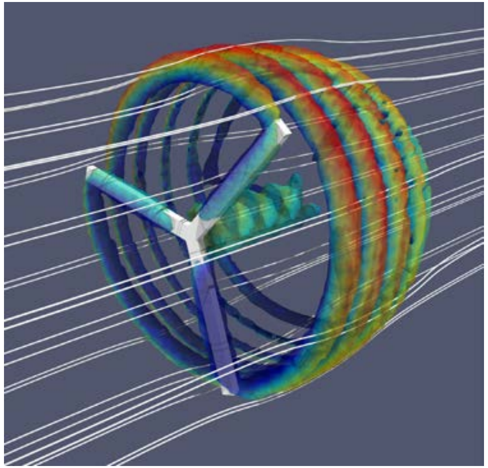
WindSE Background

- Open source, python-based, midfidelity CFD model for UQ & optimization
- RANS/LES with 2D and 3D, steady and unsteady, flat and complex terrain
- Automatic differentiation tools for gradient based optimization
- https://github.com/NREL/WindSE (Apache 2.0 license)

https://fenicsproject.org/







CFD Model and Solver

- 2D and 3D Navier-stokes with nonlinear mixing length
- No empirical wake model/superposition, or precursor simulation

Momentum: $$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\nabla p + \nabla \cdot (\nu + \nu_T)\nabla u + \boxed{\mathbf{F}}$$

Turbine force

Continuity: $$\nabla \cdot u = 0$$

Eddy Viscosity: $$\nu_T = \ell_{mix}^2 \sqrt{2\langle S, S\rangle}$$

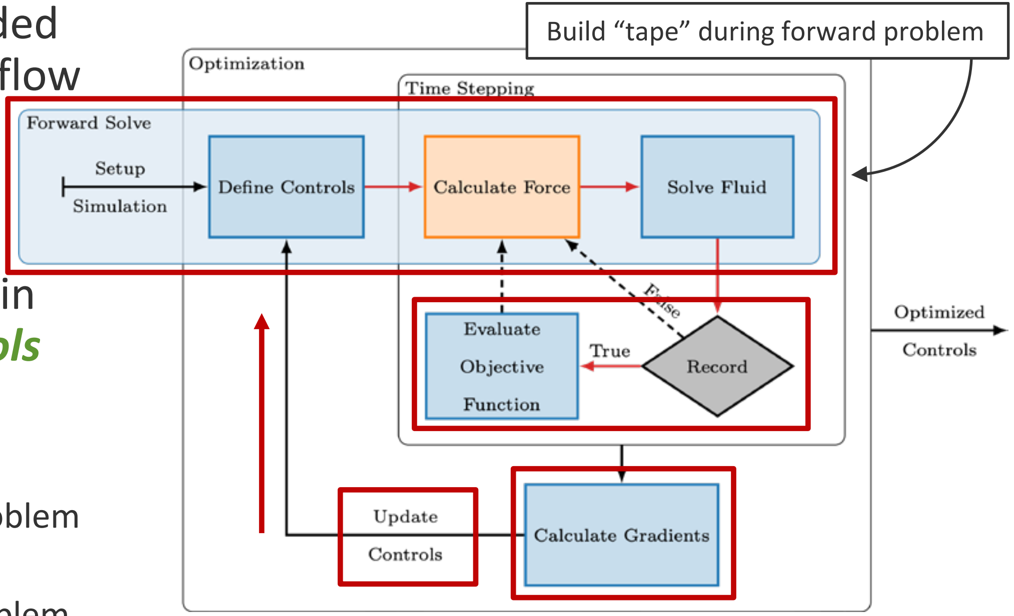
Symmetric Gradient: $$S = \frac{1}{2}(\nabla u + (\nabla u)^T)$$

Mixing Length[1]: $$\ell_{mix} = \kappa z \frac{1}{1 + \kappa z/\lambda}$$

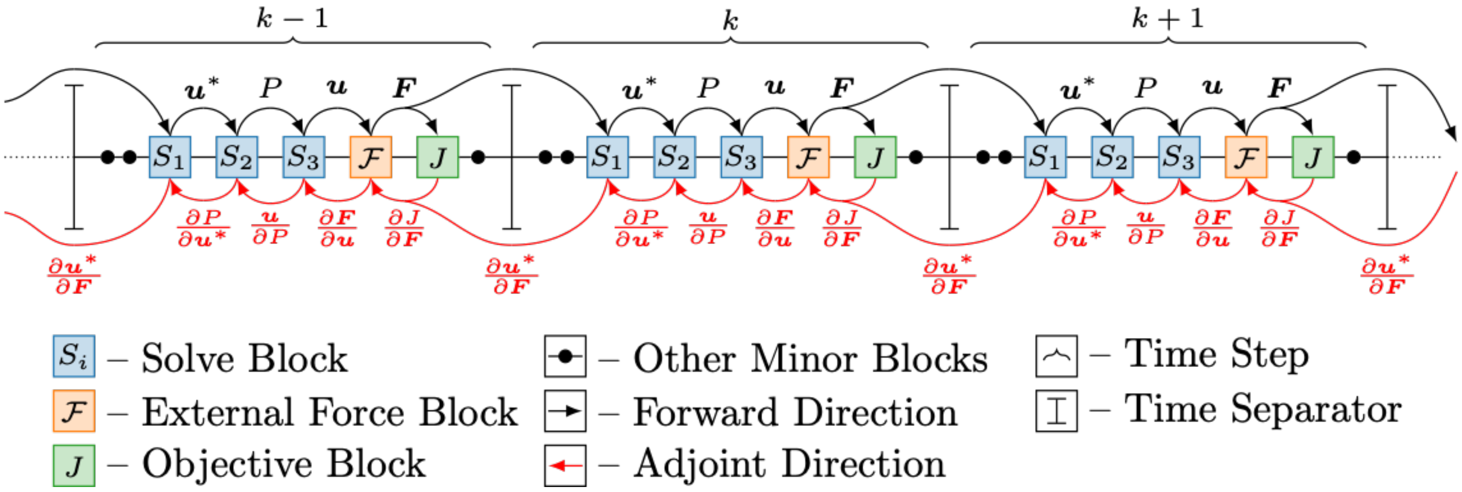
- Steady Solve - RANS w/ MUMPS
- Unsteady Solve – Pressure Correction Scheme

Methodology: Adjoint Framework

- **Forward Problem:** The sequence of finite-difference solutions are recorded during the solution of the unsteady flow
- **Adjoint Problem:** Conceptually, this sequence can propagated backward from the end of the simulation to construct the gradient using the chain rule; this gradient shows how ***controls*** affect the ***objective***
- **Optimization:**
  - Compute objective using the forward problem
  - Record **time-averaged** objective function
  - Compute gradients using the adjoint problem
  - Update the controls using the gradient
  - Repeat!


Build “tape” during forward problem

`Dolfin-Adjoint` Tape Diagram



A depiction of how `dolfin-adjoint` records the forward problem and objective function on to a tape. Then using the reverse process to propagate the gradient backwards through this tape.

For time dependent problems this is extremely expensive due to storing every time step!

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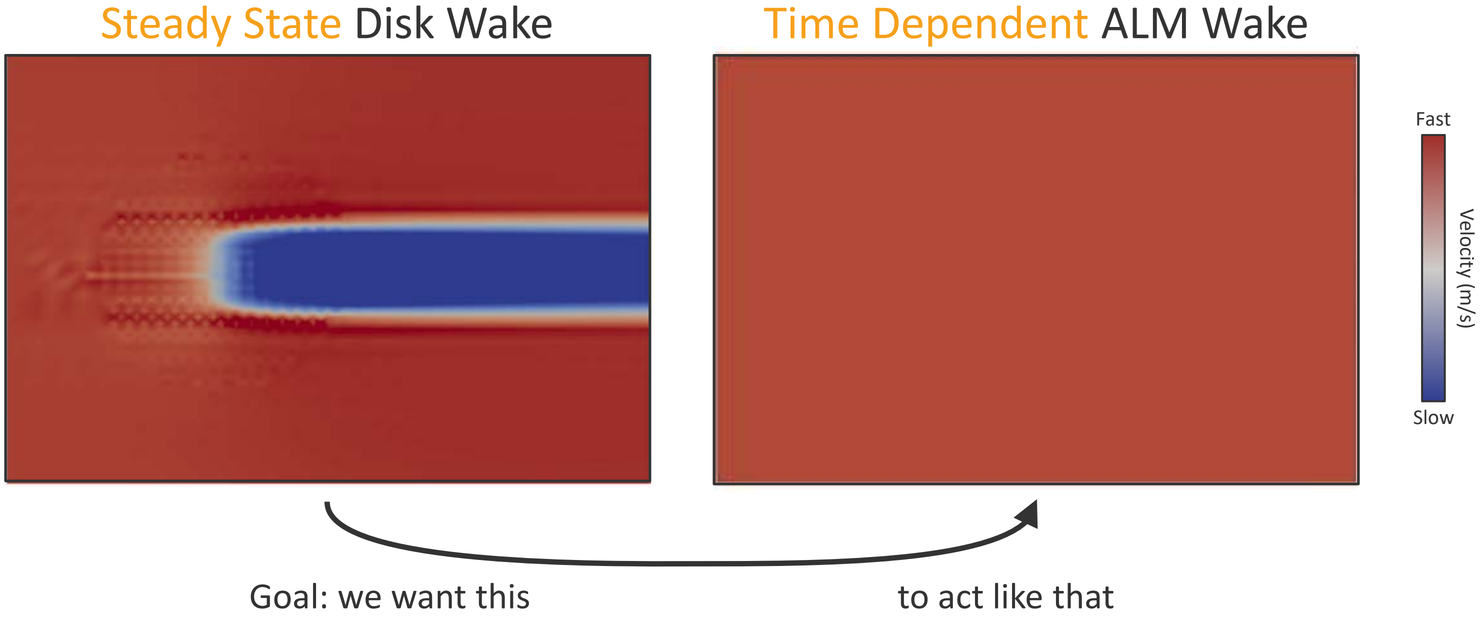
Transfer Actuator Line Dynamics to Steady State

- Because optimizing unsteady simulation is prohibitively costly, we want to investigate if there is a way to capture the average ALM dynamics with a steady state simulation.
- To that end, we will develop a “hybrid” actuator disk that can be optimized to mimic the wakes produced by an averaged ALM simulation.



Goal: we want this

to act like that

Approach: Optimizing Steady-State, Hybrid Disks

- **Goal:** Represent the effects of actuator lines in a steady state simulation.
- **Method:** Represent actuator disks as a set of nested gaussian rings. Each ring has two parameters: normal and tangent force.

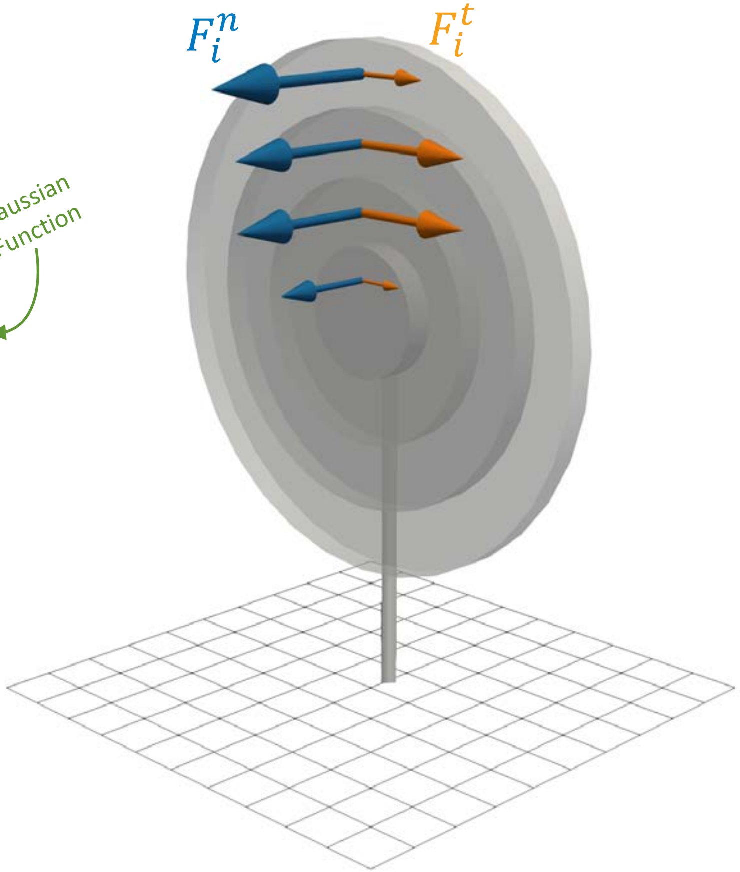
$$TF = \sum_{i=1} F_i^n \left\langle 1, \quad -\frac{F_i^t z}{r}, \quad \frac{F_i^t y}{r} \right\rangle \varphi_i(x, y, z)$$

Gaussian Function

- **Objective:** Calculate the 100 s average velocity from a 300 s ALM simulation and use that as a reference.

$$J = \left\| \left(\overline{\vec{u}_{ALM}} - \vec{u}_{disk} \right) \right\|^2$$

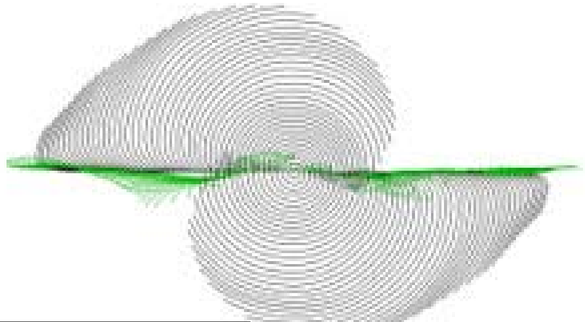
- **Optimization:** Minimize velocity difference with the normal and tangent of parameters of 4 rings as design variables.



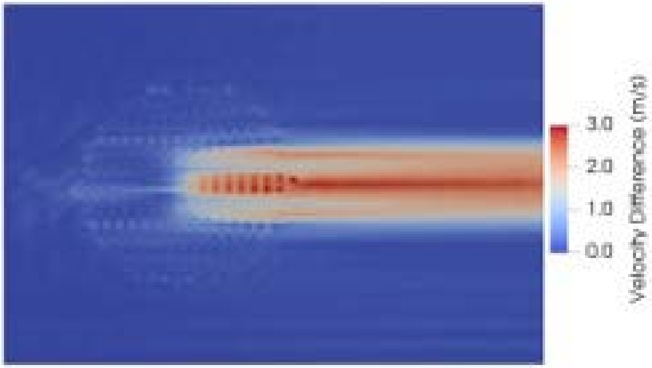
Proof-of-Concept Optimization

- The first step to testing these hybrid disks was a simple proof-of-concept test case.
- An ALM simulation was ran for 300 seconds and the final 100 seconds were averaged to get a target velocity profile.
- The optimizer then adjusted the 4 F_i^n and 4 F_i^t design variables to minimize the velocity differences between the averaged ALM wakes and hybrid disks wakes
- These videos show the results of this optimization and that the difference in wakes is reduced.
- The visualization uses streamlines to show how the hybrid disks can twist the wind similar to ALM

Streamlines viewed from downstream

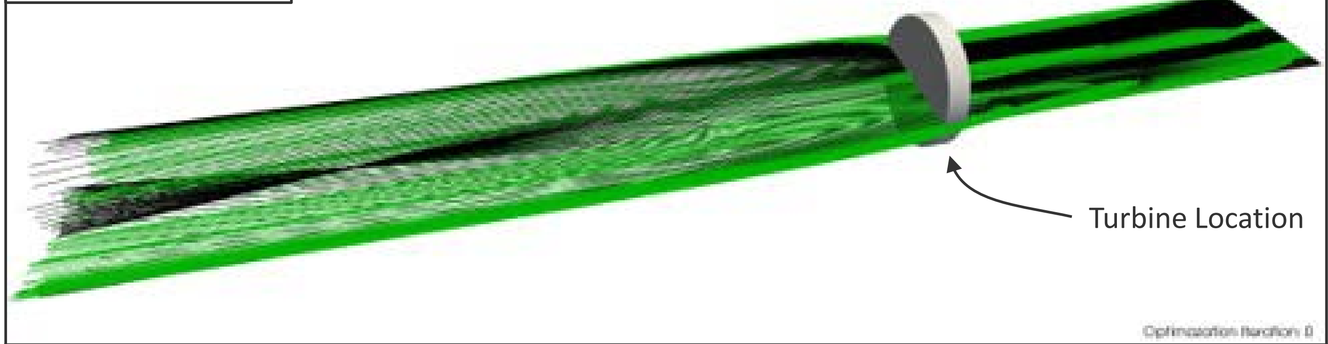


Difference between ALM and Hybrid Disks wakes



⬛ - ALM Streamlines

🟩 - Disk Streamlines



Streamlines viewed from the side with inflow on the right.

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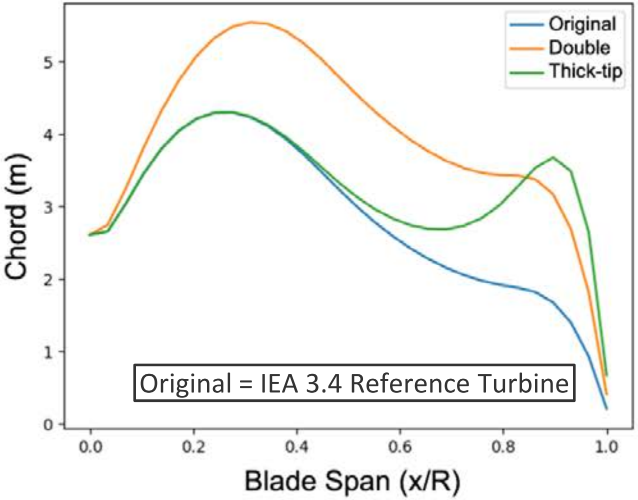
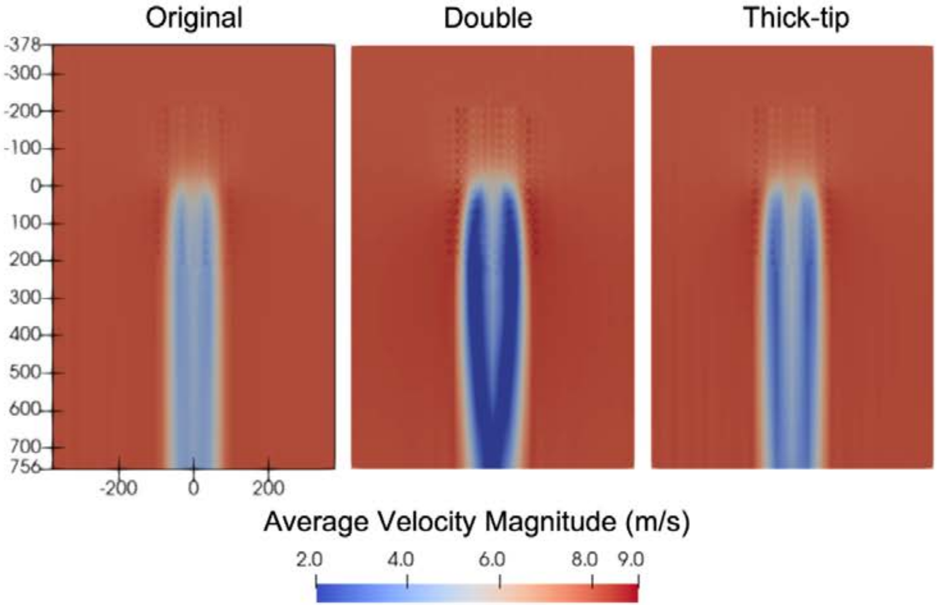
Testing Hybrid Disks with Different Chord Profiles

- This next test is aimed at seeing how they hybrid disks capture the dynamics of different ALM chord profiles.
- The ALM simulation is ran with different chord profile and the average velocity is computed using the final 100 s.
- Each chord profile produces distinctly different wake profiles.
- The hybrid disks are then optimized to match wake profiles of the averaged ALM cases.

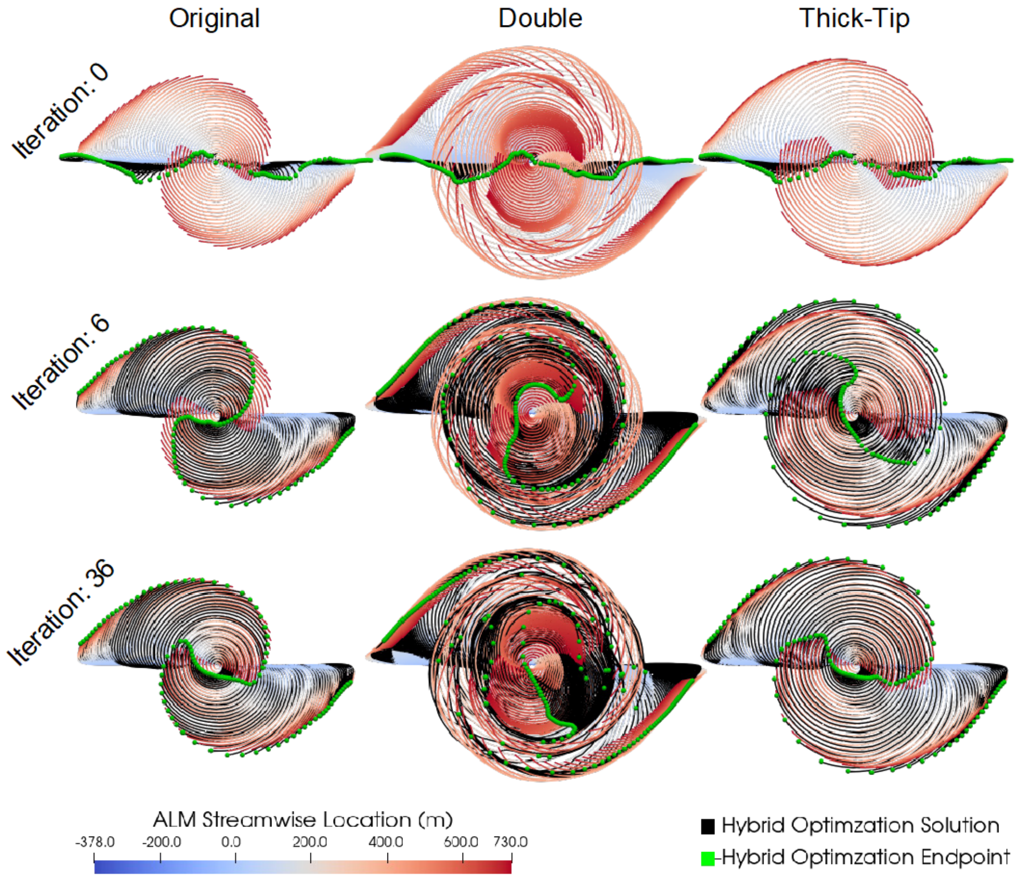


Original = IEA 3.4 Reference Turbine



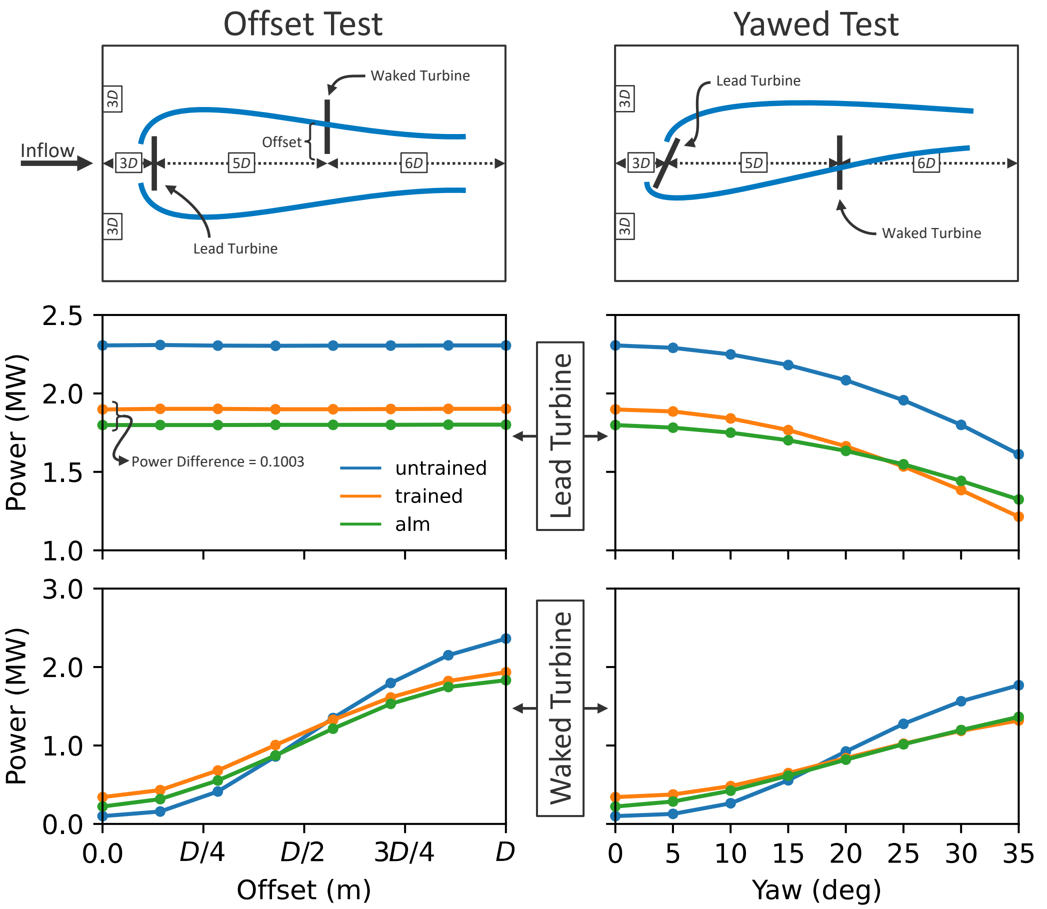
Testing Hybrid Disks with Different Chord Profiles

- Here are three snapshots of the optimization with green markers indicating the endpoint of the hybrid disk streamlines.
- Hybrid disk can capture the “original” and “thick-tip” profiles quite well.
- The double profile might be out of range for the capabilities of the hybrid disks.
- It is interesting to see that in iteration 6, the Thick-tip optimization “overshoots” but recovers by the final iteration.



Robustness study

- This test is designed to see how the wakes of the optimized hybrid disks interact.
- Ideally, only one optimization is needed to accurately predict how multiple turbines interact.
- The offset test places two turbines in a wake position and shifts the back turbine up and out of the wake of the leading turbine.
- The yawed test uses the same turbine configuration but wakes the leading turbine to test wake steering.
- Both the offset and wake tests show good agreement between the optimized and ALM cases.
- A small power difference of ~0.1 MW can be seen in the leading turbines of the offset case.



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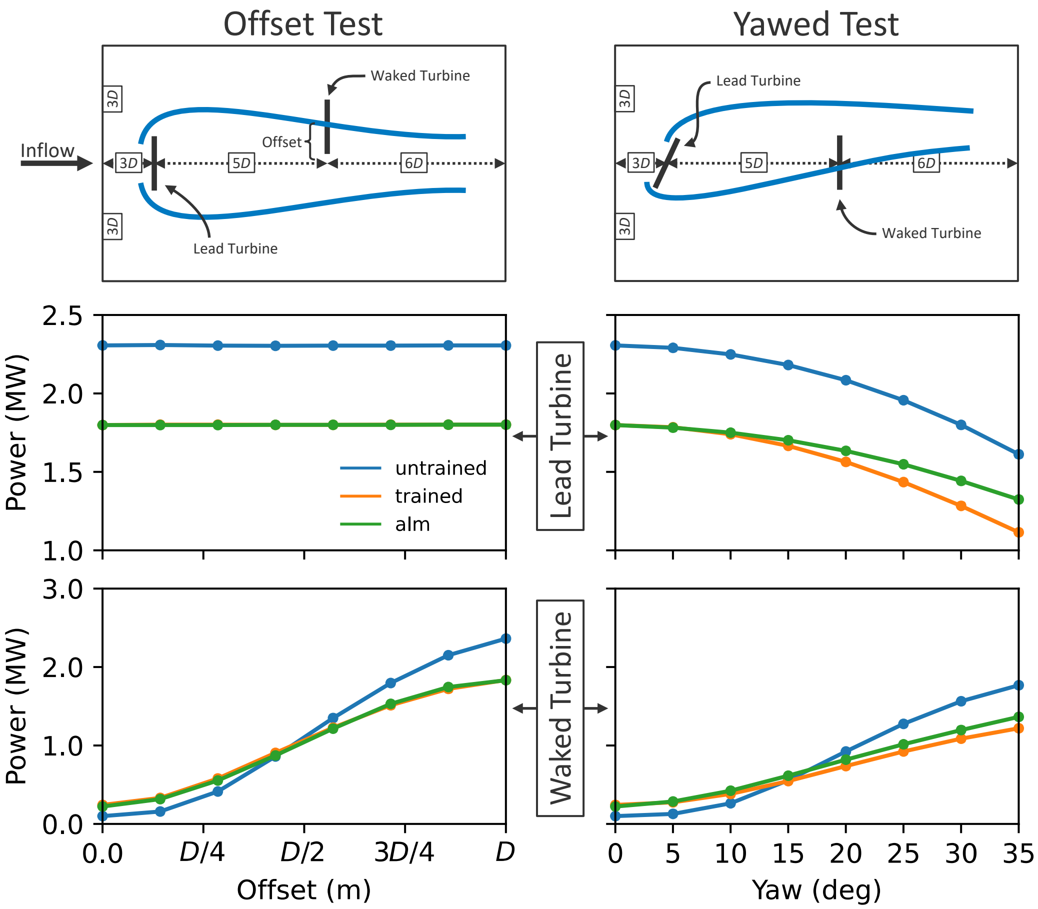
- A small power difference of ~0.1 MW can be seen in the leading turbines of the offset case.
- The hybrid disk power can be further calibrated by subtracting off this power difference
- This shows even better agreement for the offset case but reveals that the hybrid disks systemically under predict the ALM case.
- More research is need to perfect the hybrid disks



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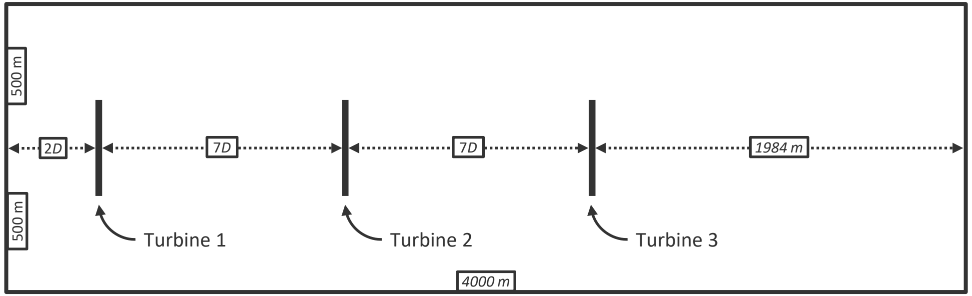
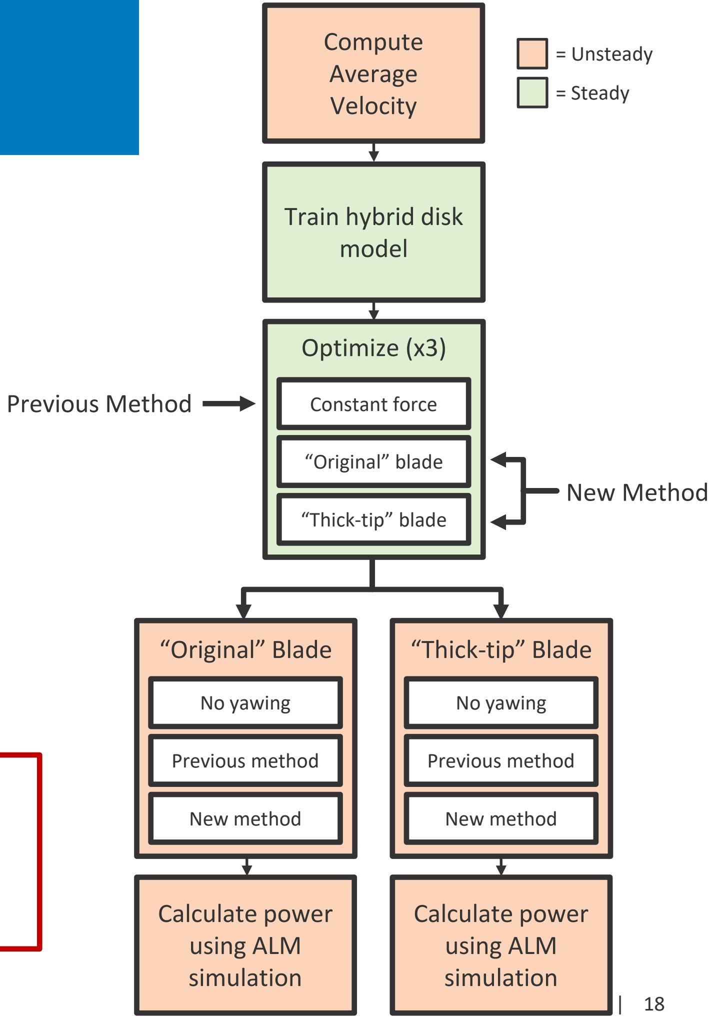
Yaw Optimization: Setup

- Could not be done with ALM alone (too expensive)
- Wind farm setup*
- Optimize power by changing yaw



Expectation: Hybrid disk yaw strategy produces more power than the previous method's yaw strategy when used in an unsteady simulation.



🟧 = Unsteady
🟩 = Steady

Compute Average Velocity

Train hybrid disk model

Optimize (x3)
- Constant force
- "Original" blade
- "Thick-tip" blade

Previous Method

New Method

"Original" Blade
- No yawing
- Previous method
- New method

"Thick-tip" Blade
- No yawing
- Previous method
- New method

Calculate power using ALM simulation

Calculate power using ALM simulation

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*King, Jennifer, Fleming, Paul, King, Ryan, Martinez, Luis A., Bay, Christopher J., Mudafort, Rafael, and Simley, Eric. *Control-Oriented Model for Secondary Effects of Wake Steering*. United States: N. p., 2021. Web. doi:10.5194/wes-6-701-2021.

Yaw Optimization: Steady Results

- Note: we cannot compare power directly since each forcing function produces different power profiles.
- Not much of a difference
- Largest difference in middle turbine

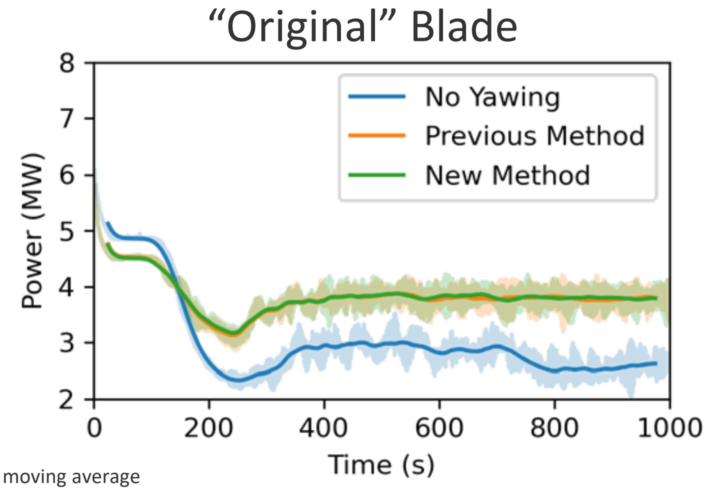
Yawing Strategies

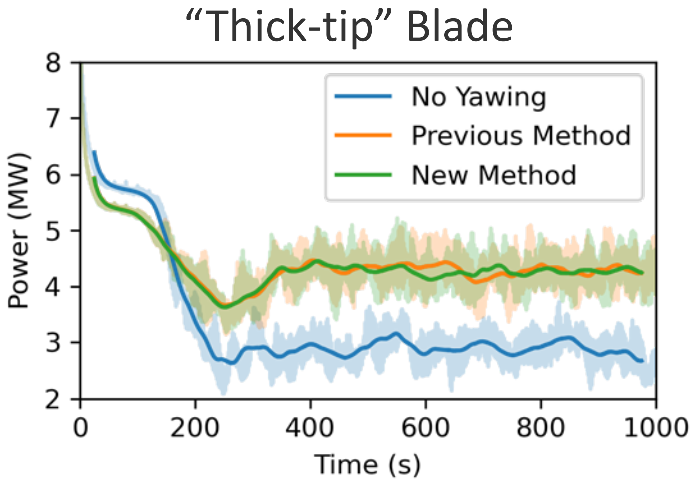
	Turbine 1	Turbine 2	Turbine 3
Constant Force	29.05°	10.13°	-3.09°
“Original” Blade	29.18°	11.44°	-3.01°
“Thick-tip” Blade	29.66°	9.11°	-3.41°

Yaw Optimization: ALM Results

Same blade properties
Different yaw strategies

- Check if hybrid disk yaw strategy > constant force strategy
- Conclusion #1: Yawing is better!
- Conclusion #2: New method created deviation but not very significant.
- Conclusion #3: “Thick-tip” produces more power with higher variability.

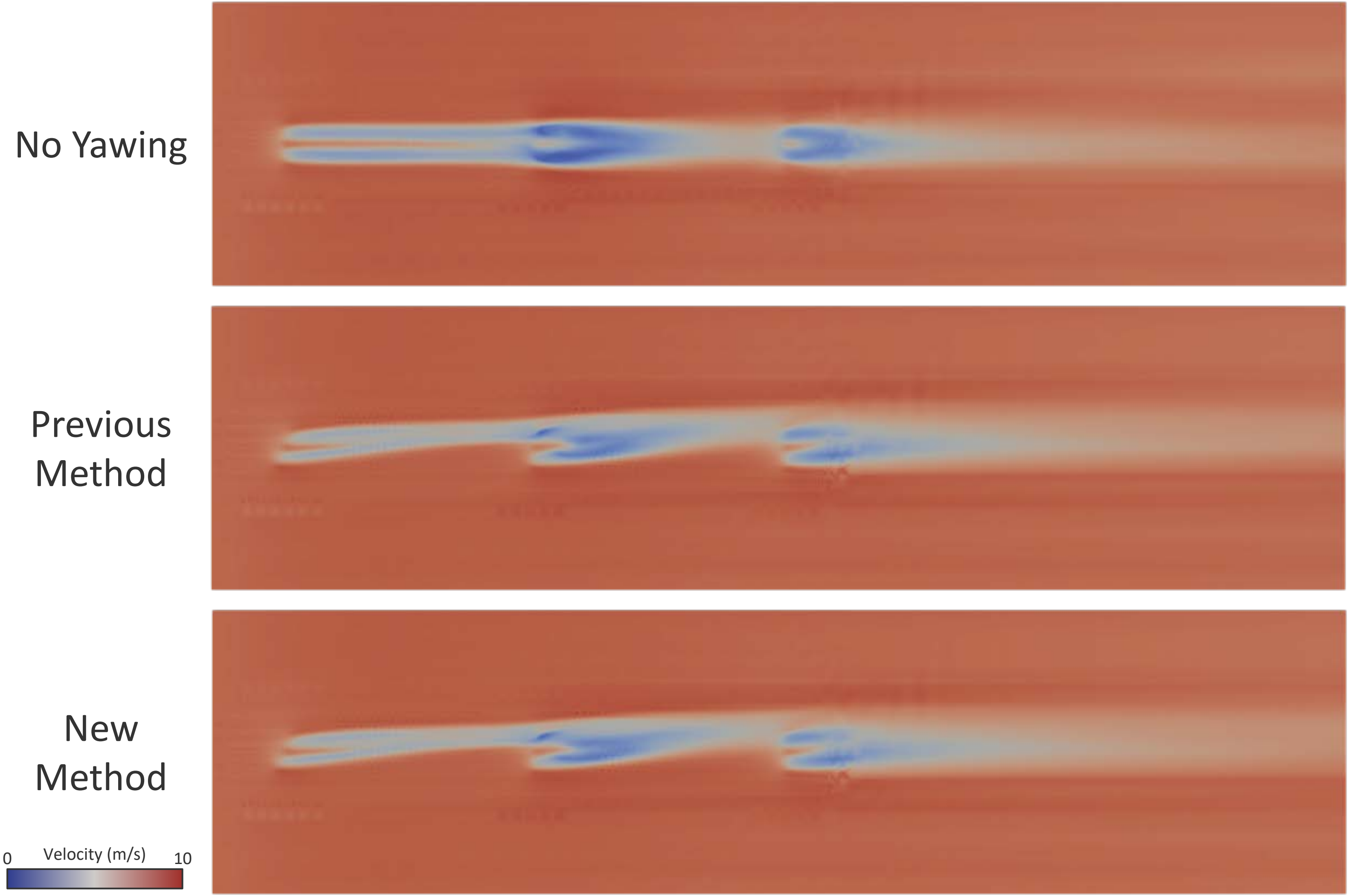




Smoothing: 50 second moving average

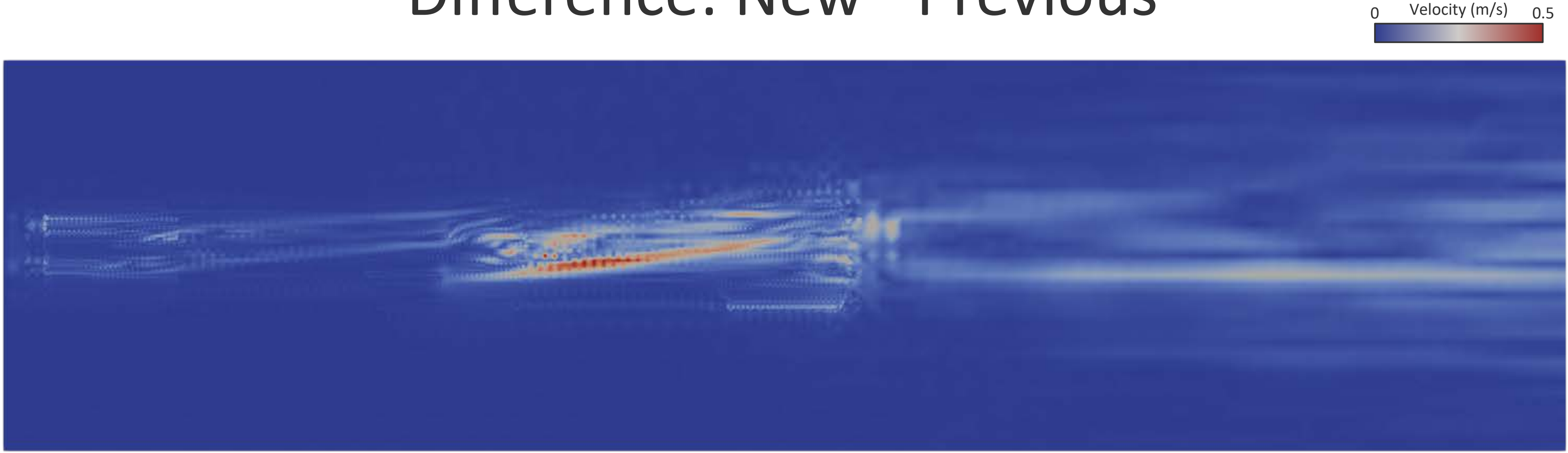
Comparing ALM Simulations

“Original” Blade



Checking out the slight differences

Difference: New - Previous

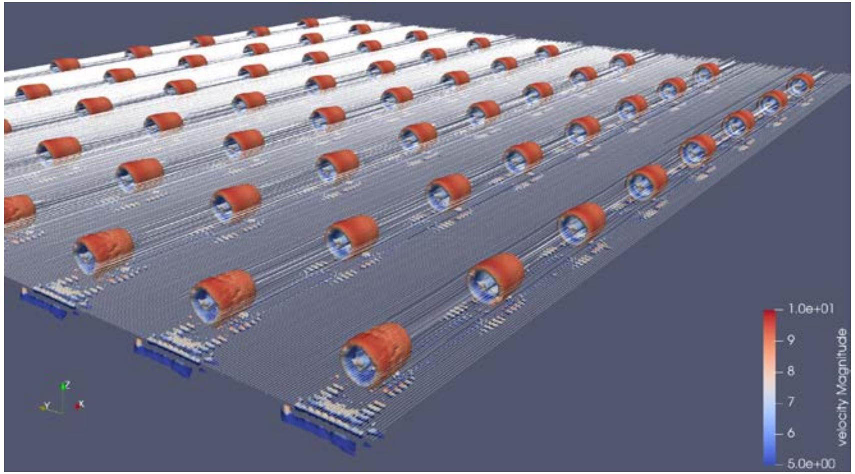


Red indicates where the velocity is faster using the hybrid disk’s yaw strategy

Outline

Future

- Conclusions:
  - Hybrid disks can capture the vorticity of unsteady simulation
  - Yaw optimization are not sensitive to vorticity effect (simple steady simulation sufficient)
  - Can anyone think of an optimization where vorticity really matters?
- Future work - Hybrid disks:
  - Train with multiple yaw angles
  - Train with longer wakes
  - Different optimization
- Future work - General:
  - Improve performance
  - Simulate larger wind farms
  - Play around with cool objective functions and controls



Thanks for coming!

Questions?

Contact info: Jeff.allen@nrel.com

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