Progress on optimizing wind farms and rotor designs using adjoints

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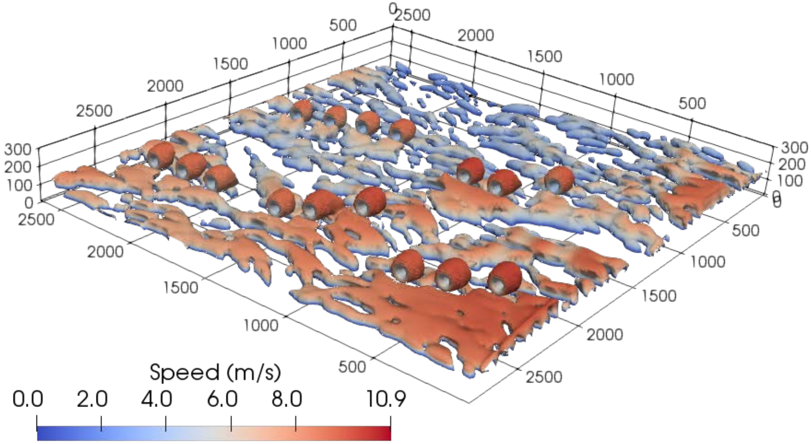
WindSE Background

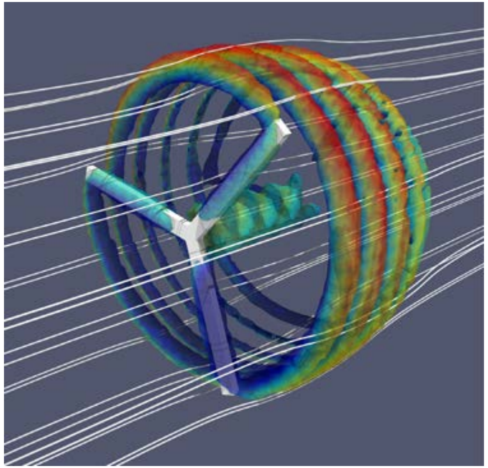
- Open source, python-based, midfidelity CFD model for UQ & optimization
- RANS/LES with 2D and 3D, steady and unsteady, complex terrain capabilities
- Hosted at https://github.com/NREL/WindSE
- Collaborators (A-Z):

WETO
- Garrett Barter
- Pietro Bortolotti
- John Jasa

CSSO
- Ryan King
- Kinshuk Panda
- Ethan Young

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

Turbine force

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

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

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

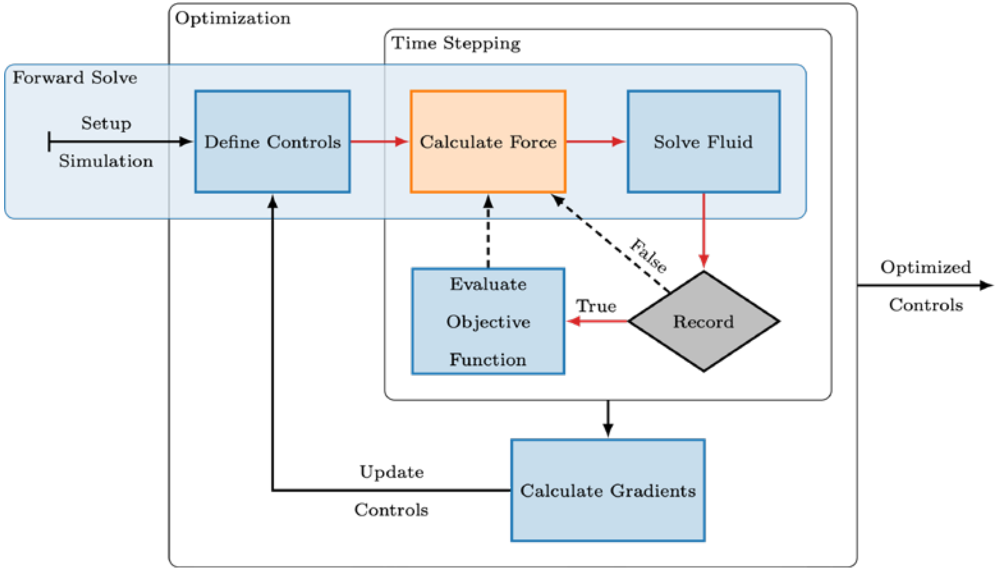
Mixing Length[1]: $$\ell_{mix} = \kappa z \frac{1}{1 + \kappa z/\lambda}$$

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

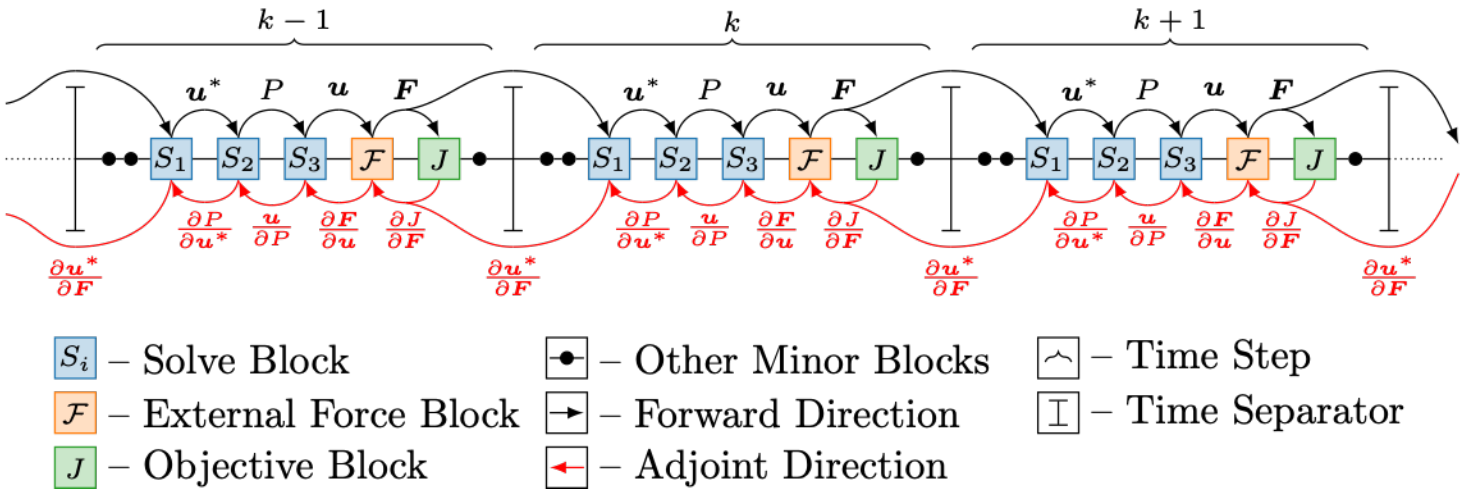
[1](Blackadar, 1962)

Methodology: Adjoint Framework

- **Forward Solve:** The sequence of finite-difference solutions are recorded during the solution of the unsteady flow
- **Adjoint Solve:** 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*



`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.

Chord Optimization

Unsteady Simulation

Actuator Lines

Fixed Turbine Position

Turbine Force: Actuator Lines

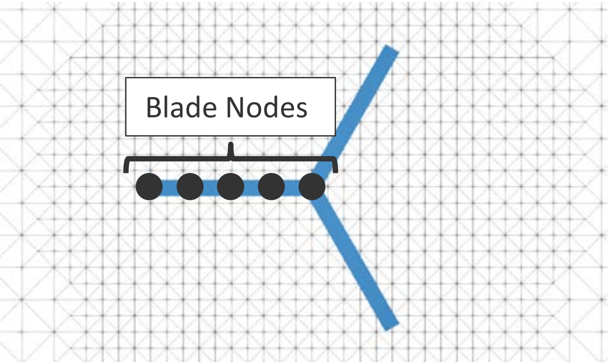
Basic Idea: A summation of point forces projected onto small, spherical, Gaussian distributions positioned to model discrete rotor blades

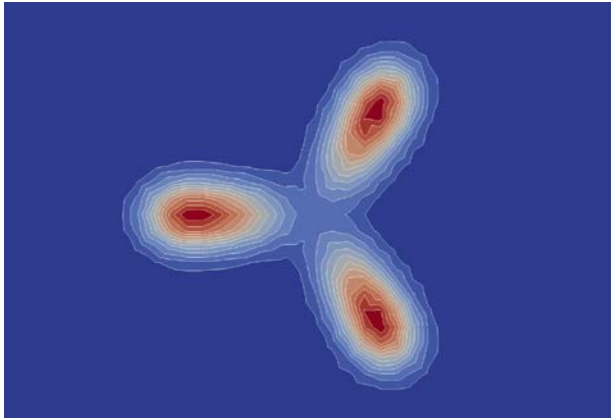
$$\boldsymbol{F}(x,y,z,t) = -\sum_{j=1}^{N} \boldsymbol{f}_j(x_j,y_j,z_j,t)\frac{1}{\varepsilon^3\pi^{3/2}}\exp\left(-\frac{|\boldsymbol{d}_j|^2}{\varepsilon^2}\right)$$

$$L(x,y,z,t) = \frac{1}{2}C_l\rho c w|\boldsymbol{u}_{rel}(x,y,z,t)|^2$$

$$D(x,y,z,t) = \frac{1}{2}C_d\rho c w|\boldsymbol{u}_{rel}(x,y,z,t)|^2$$

Chord Length



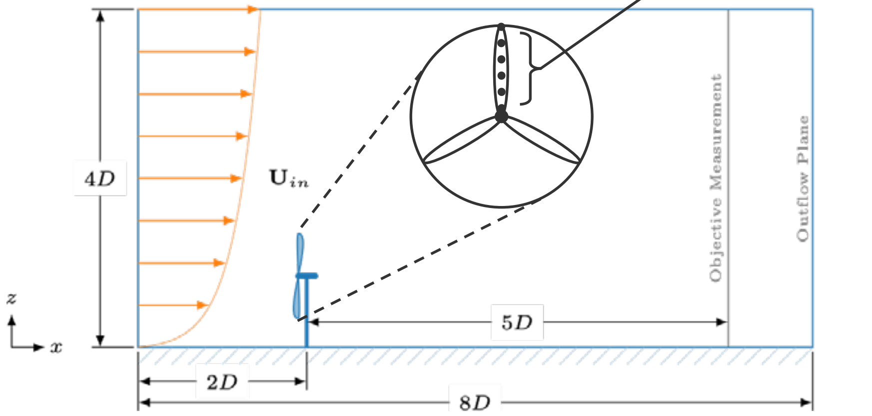


Wake Deflection Study: Setup

Goal: optimize chord profile to maximize wake deflection

Setup: Single IEA 3.4 MW turbine yawed at 20° simulated for 250 seconds

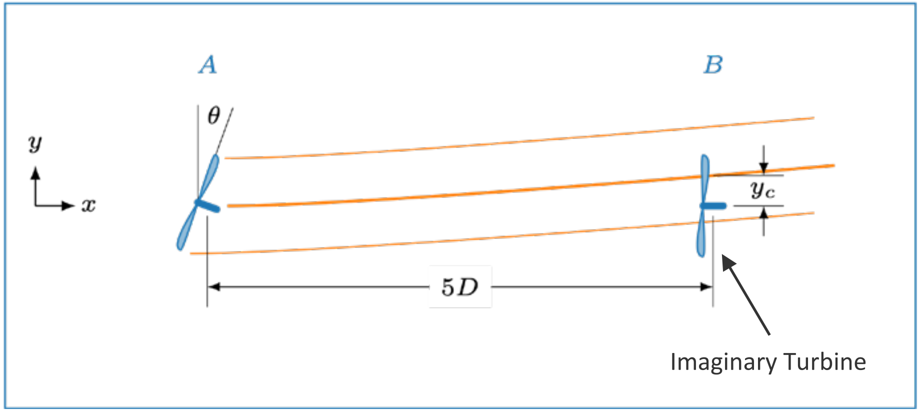
Controls: Chord length at each blade node



Objective Function: wake centroid at 5D downstream averaged from 200 s to 250 s

$$y_c = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{\int_{x=5\mathrm{D}} y_i u_{\mathrm{wd}} \, dA}{\int_{x=5\mathrm{D}} u_{\mathrm{wd}} \, dA} dt$$

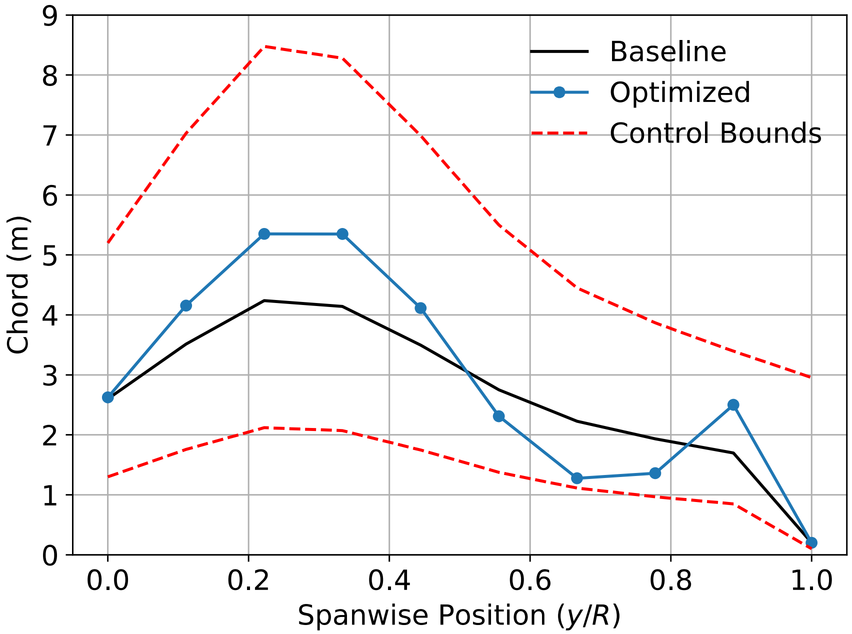
$$u_{\mathrm{wd}} = \left| \mathbf{u}_{inflow} - \mathbf{u} \right|$$



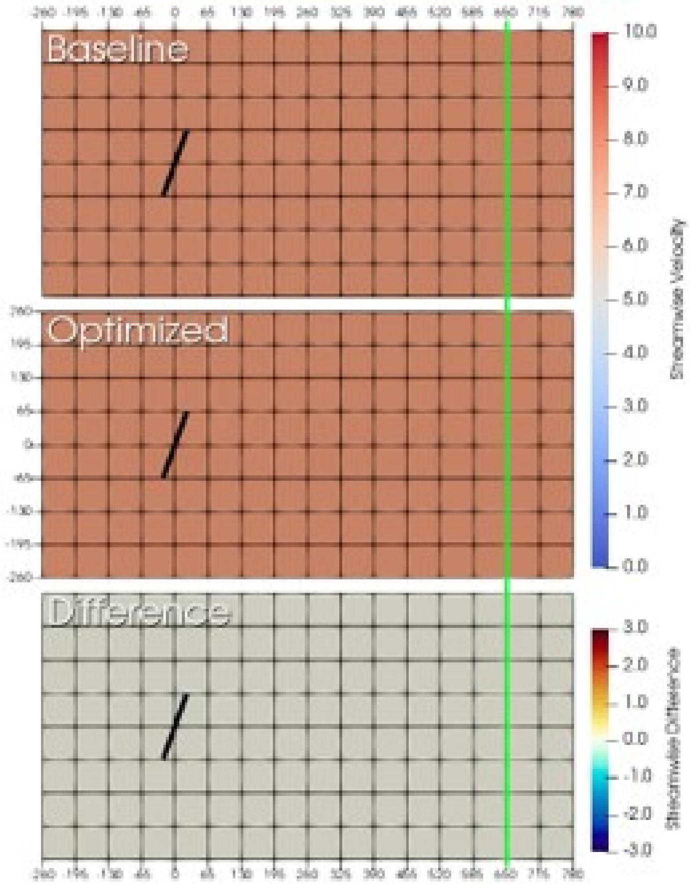
Wake Deflection Study: Results

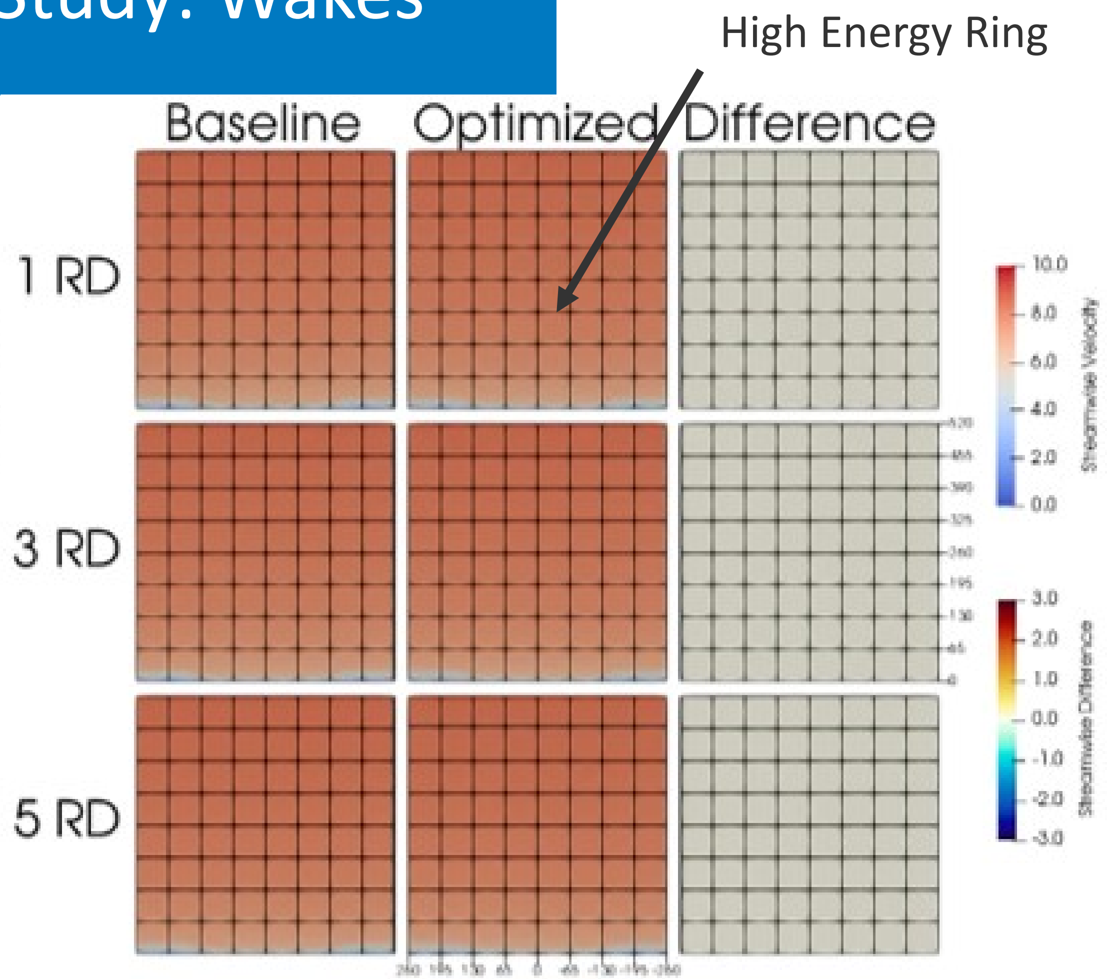
- Tip and root node exhibit little to not sensitivity
- Chord can influence centroid location but with little control authority

DOFs	Case	Deflection (m)	% Change
178K	Baseline	25.51	
	Optimized	27.48	+7.72%
1152K	Baseline	27.05	
	Optimized	28.18	+4.18%



Wake Deflection Study: Wakes

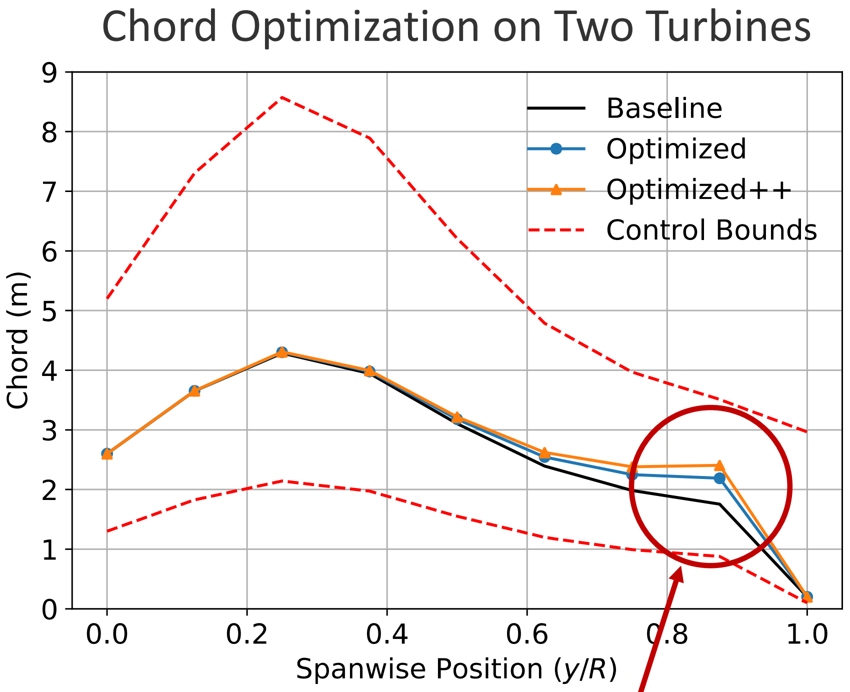




Summary & Future

Summary

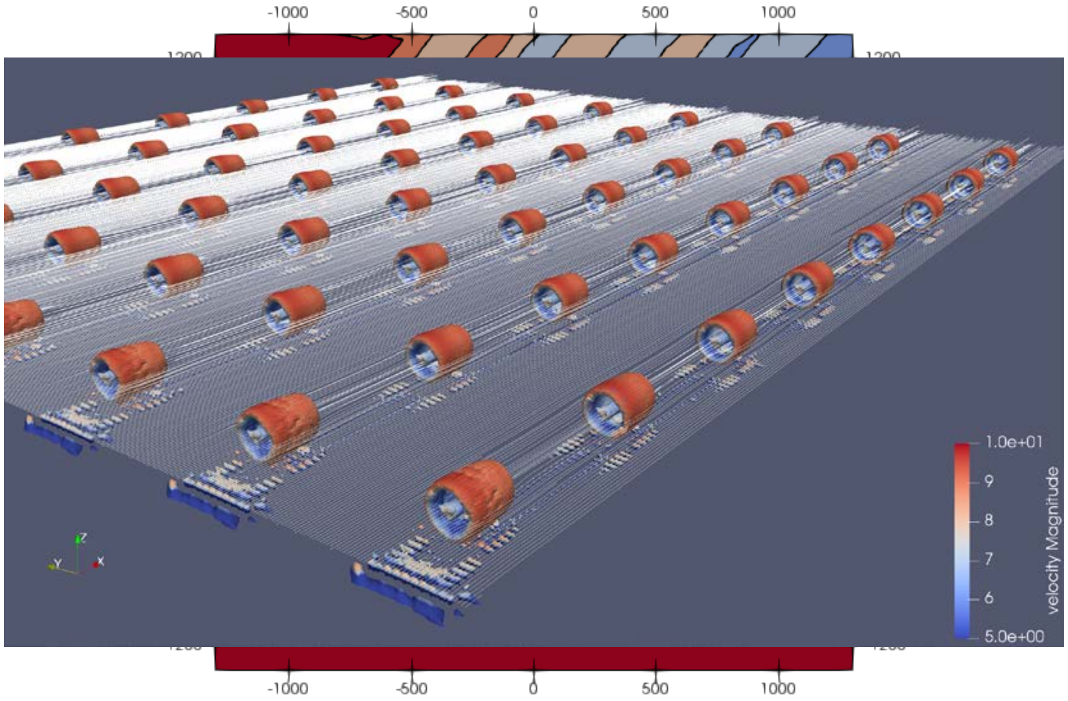
- Design Variables:
  - Turbine Position
  - Yaw
  - Chord Length
- Objective Functions:
  - Wake Centroid
  - Kinetic Entrainment
  - Actuator Line Power
  - Actuator Disk Power



Bump in chord => ~2% Power increase

Future

- Parallelization:
  - 64-turbine farm
  - 32M total degrees of freedom
- Blockage Study:
  - Investigate blockage effects from large scale wind farms
  - Perform layout optimization to minimize blockage



Thanks for Coming!

For additional questions feel free to email me: jeff.allen@nrel.gov

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