Offshore Turbine Arrays: *Numerical Modeling and Experimental Validation*

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Motivation

- **Upwind turbines affect downwind turbine:**
  Performance, Loads, Wakes
- **Economic consequences:**
  - Decrease in performance
  - Loss of energy production up to 20%
- **Increased turbulence**
  - Fatigue loading on rotors
  - Varying loads on gearbox
  - Decreased life span
  - Increased O&M costs
- US DOE goal: Produce 20% of electric energy from wind by 2030
- Array experiments are performed at the UNH Flow Physics Facility
- Numerical model can be used to predict/validate results and decrease experimental efforts and costs

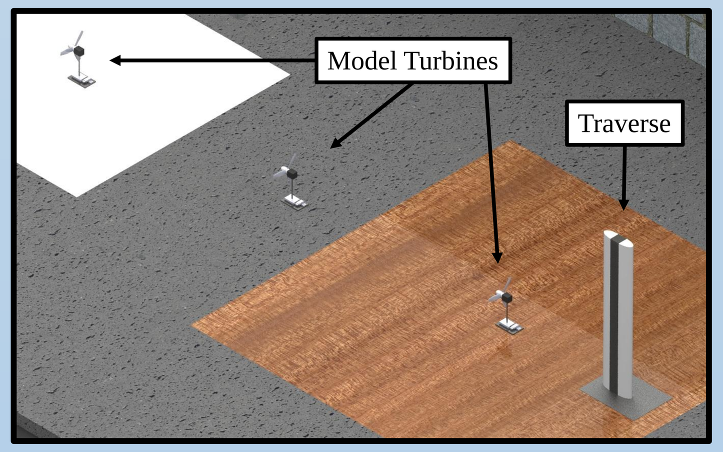
Horns Rev 1, Inset: Normalized power at each turbine in a central row at Horns Rev 1 (Barthelmie et al, 2009)

Experimental Data

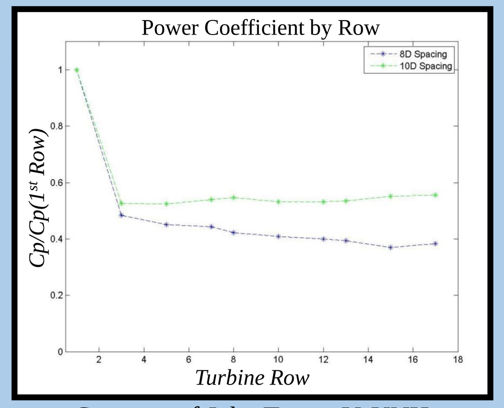
Scale Model Turbines
- Rotor diameter of 0.25 m
- Hub height 0.75 D (1:500 scale)
- NACA 2412 airfoils
- Anaheim Automation DC motor
- Force balance stand to measure drag force

Porous Disks
- Experimental tool, saves cost when modeling many turbines
- Diameter of 0.25 m
- Hub Height 0.75 D
- Porosity of 0.48
- Wake similarity 8D downstream

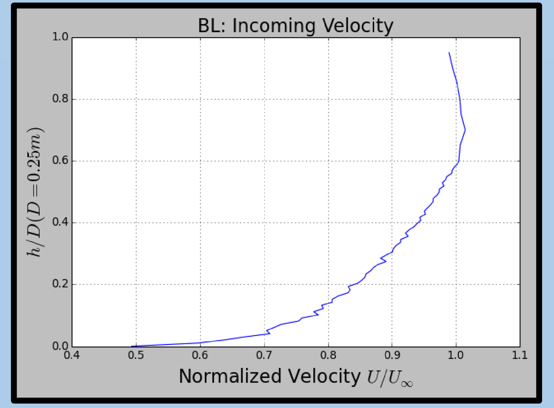
Data Collection



- Velocity and turbulence intensity measurements from hot-wire
  - Profiles of wind tunnel inlet and profiles behind turbine and porous disk
- Drag measurements taken with load cells
  - Coefficient of power for first and downstream turbines



Courtesy of John Turner V, UNH



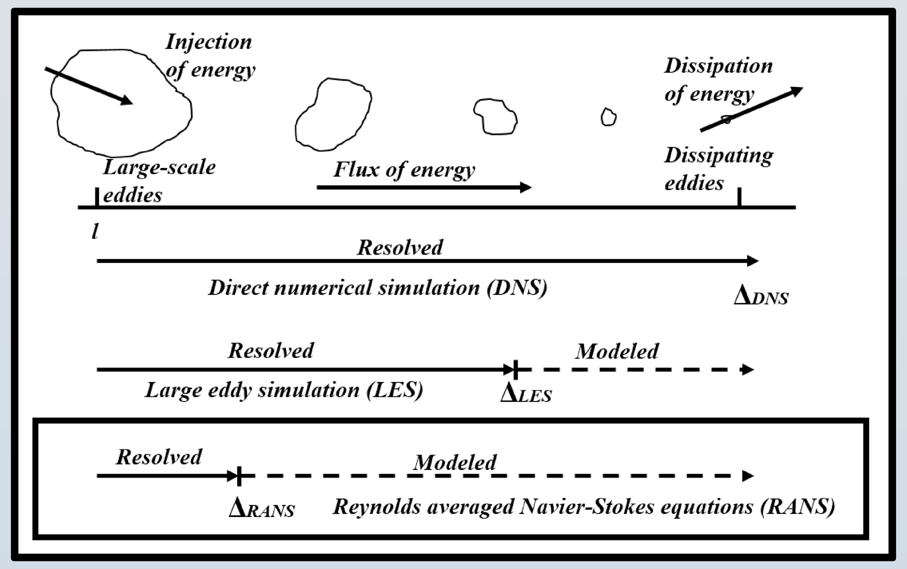
Computational Fluid Dynamics (CFD)

- Turbines modeled as actuator disks
- Turbulence modeling. Two equation model
- Flow in box → single turbine → arrays
- At each step, numerical results compared to experimental data
- Model parameters analyzed and modified

Varied Parameters
k, Turbulence kinetic energy
ℓ, Length scale
ε, Kinetic energy dissipation
I, Turbulence intensity
Mesh refinement
Boundary Conditions

RANS Modeling (k-ε)

- Reynold's Averaged Navier Stokes equations
- Effects of turbulence on the mean flow
- Model Reynolds stresses through transport equations for k and ε



RANS Equations:

⟶ $\frac{\partial \bar{v}_i}{\partial x_i}=0$ Continuity Equation

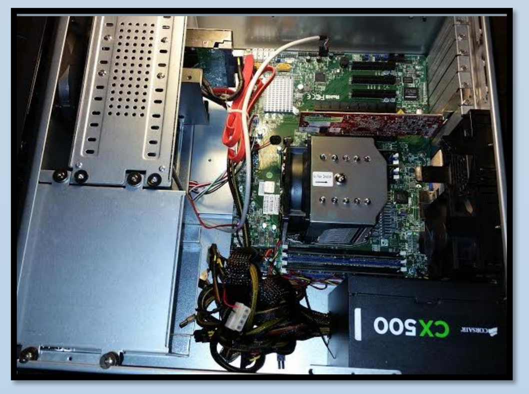
⟶ $\rho\left(\frac{\partial \bar{v}_i}{\partial t}+\bar{v}_j\frac{\partial \bar{v}_i}{\partial x_j}\right)=-\frac{\partial \bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\overline{\tau_{ij}}-\rho\overline{v_i'v_j'}\right)$ Momentum Equation

⟶ $\frac{\partial(\rho k)}{\partial t}+\nabla(\rho k U)=\nabla\left[\frac{\mu_t}{\sigma_k}\nabla k\right]+2\mu_t S_{ij}*S_{ij}-\rho\varepsilon$ Kinetic Energy Transport Equation

⟶ $\frac{\partial(\rho\varepsilon)}{\partial t}+\nabla(\rho\varepsilon U)=\nabla\left[\frac{\mu_t}{\sigma_\varepsilon}\nabla\varepsilon\right]+C_{1\varepsilon}\left(\frac{\varepsilon}{k}\right)2\mu_t S_{ij}*S_{ij}-C_{2\varepsilon}\rho\left(\frac{\varepsilon^2}{k}\right)$ Dissipation Equation

Open-Sourced Engineering

- Ubuntu – Necessary for OpenFOAM
- OpenFOAM – CFD C++ Toolbox
- Paraview – Data viewer
- Python – Post processing
- Git – Version control system
- Github – Source code hosting and sharing



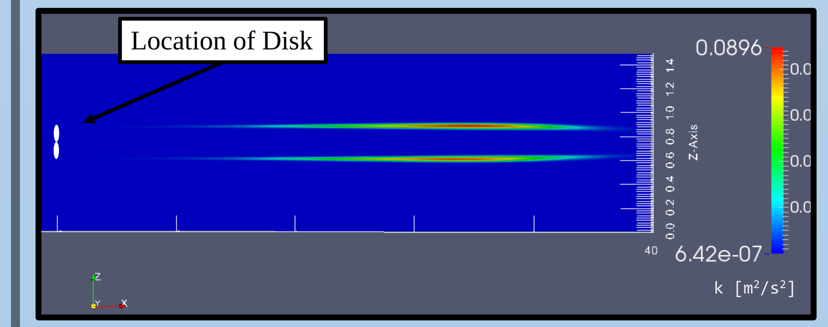
Simulations run on custom built server designed as head node of small future CFD cluster

Scan for case files

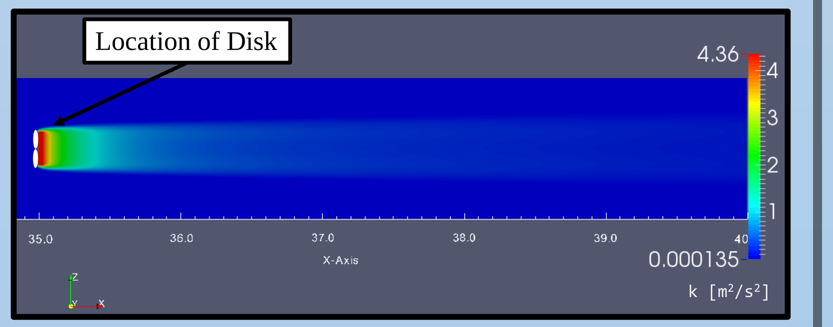
OpenFOAM Numerical Model

Turbulence Injection (k and ε):

No k injection



With k injection

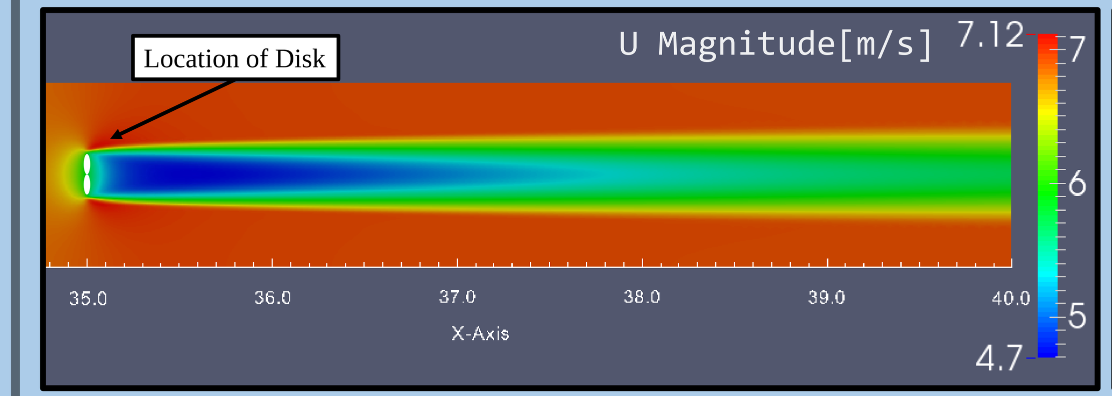


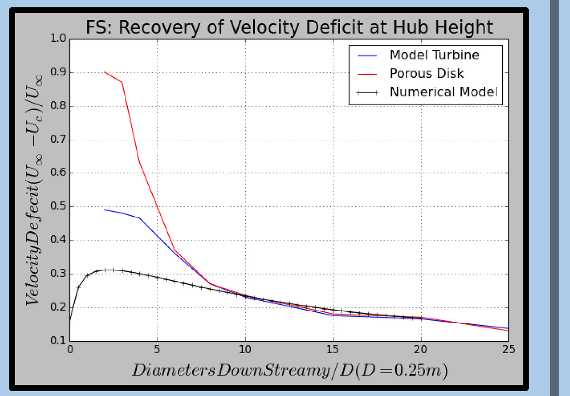
- Blades not resolved with actuator disks so less turbulence in wake
- Only turbulence due to shear from the velocity gradient at wake boundaries

→Velocity recovers too slowly due to decreased mixing

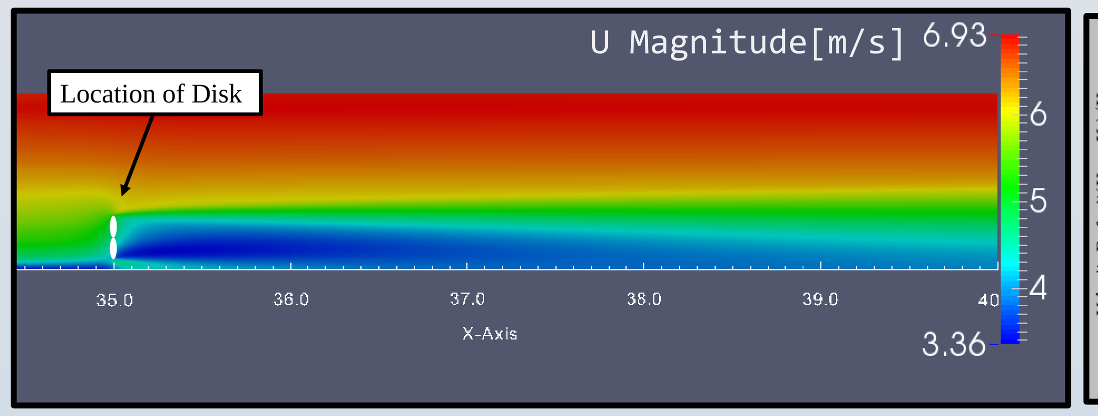
→Necessary to inject turbulence at the actuator disk

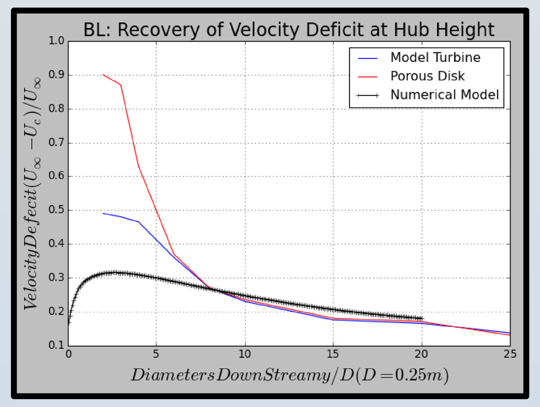
Actuator Disk: *Freestream (FS)*

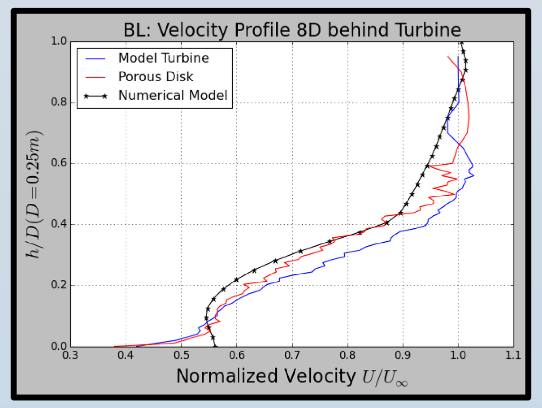


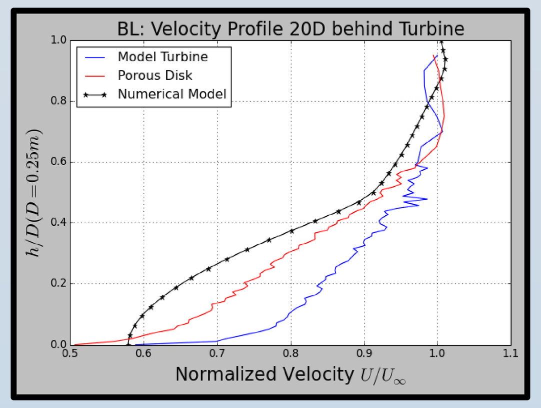


Actuator Disk: *Boundary Layer (BL)*

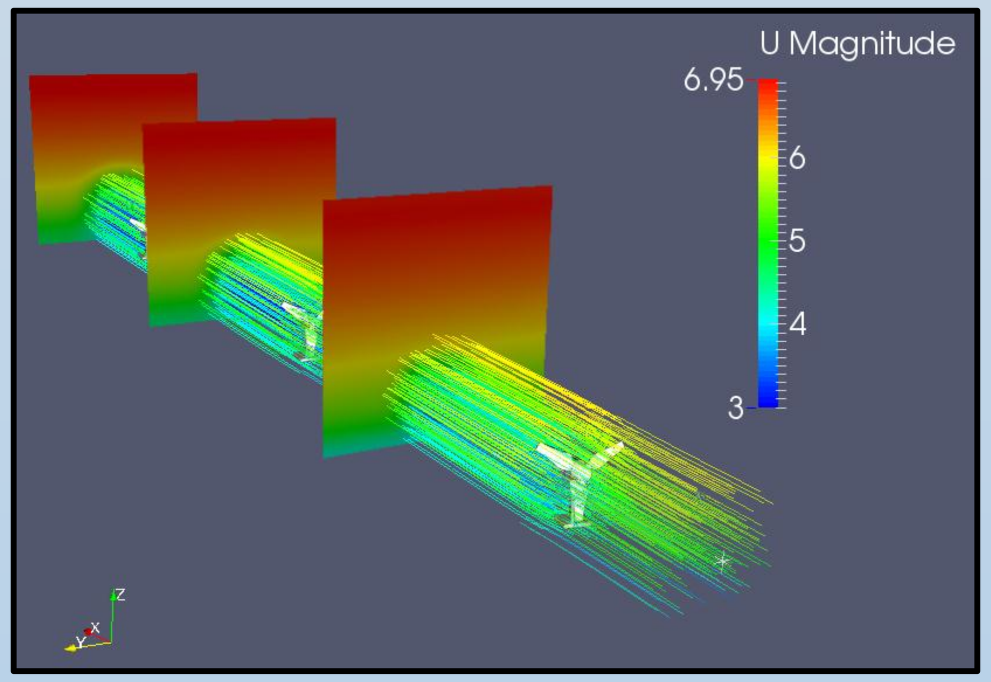




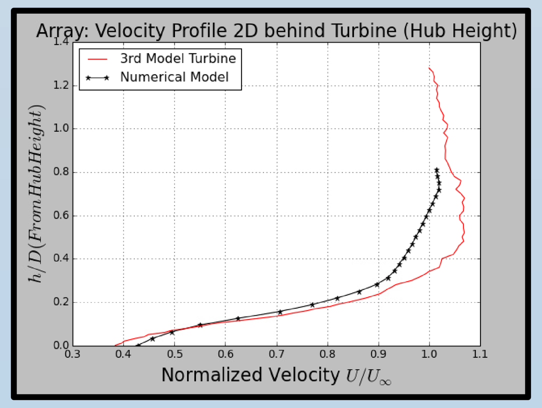


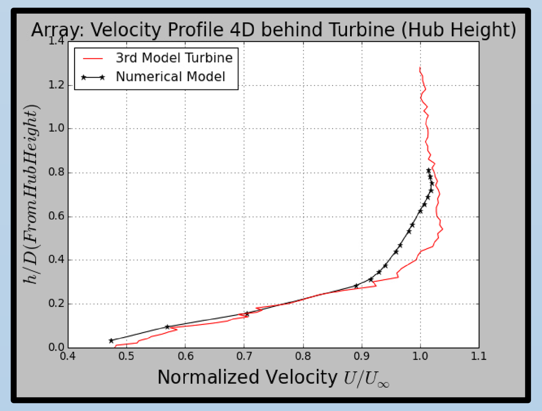


Actuator Disk Array: *Boundary Layer*

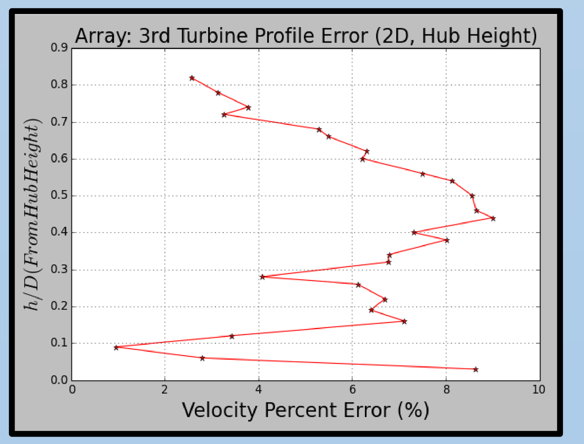


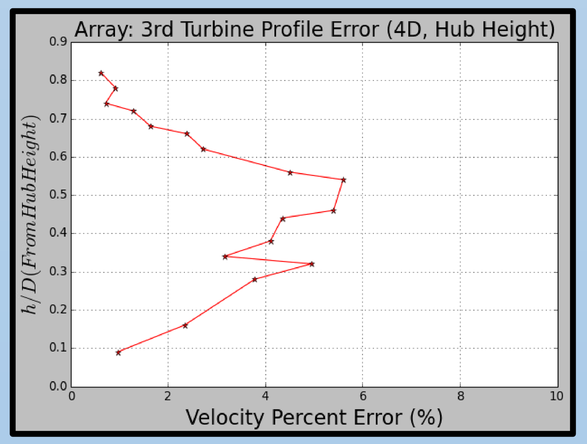
- 3 by 1 turbine array modeled in BL
- 8D turbine separation





Outcomes





Percent difference for 3rd row turbine velocity profile
- Less than 10% at 2D
- Less than 6% at 4D

Framework for studying turbine arrays was developed

Future Work
- Develop actuator line model for increased model accuracy
- Improve computational power of CFD cluster
- Apply model to larger arrays
- Algorithm for turbine array optimization

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