WESEP 594 Research Seminar

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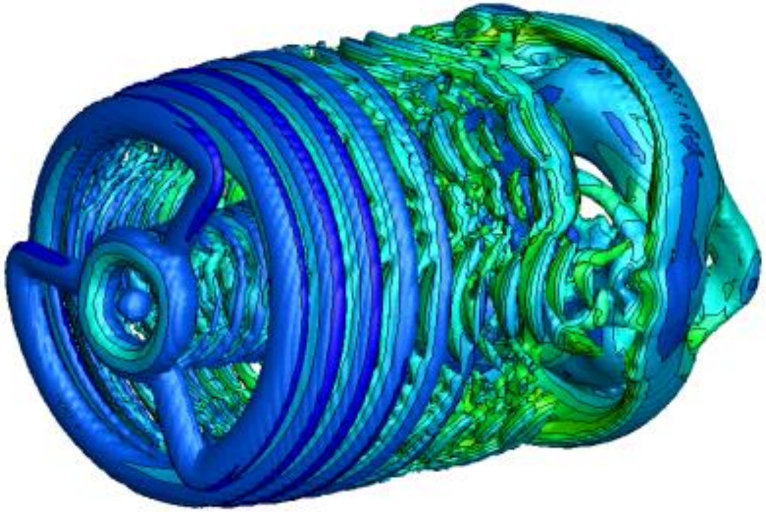
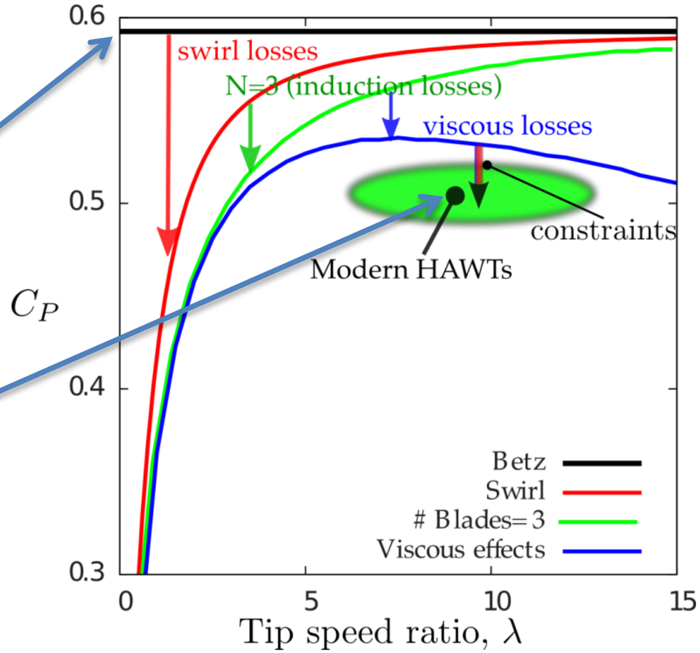


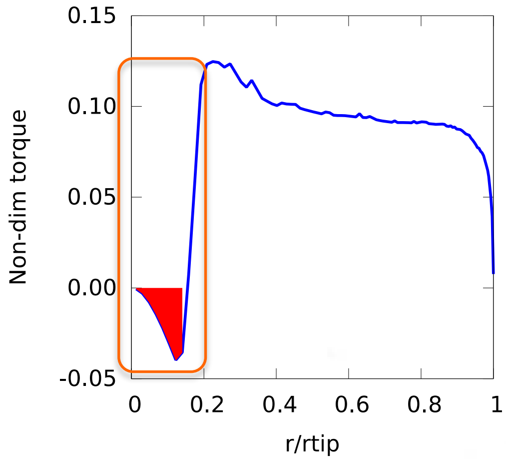
Major: WESEP

Co-major: Aerospace Engineering

Motivation

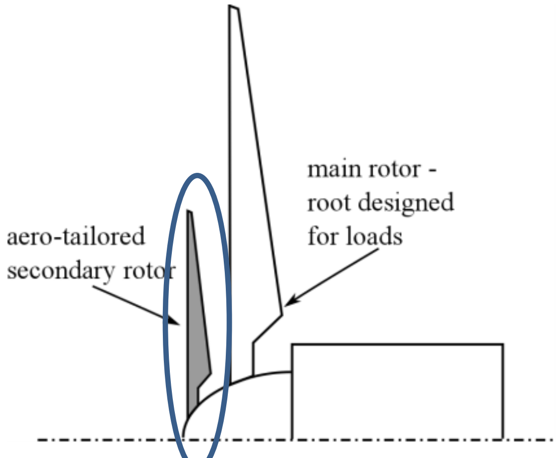
- **Increase Wind Energy Capture**
- Betz limit:
  - 59.3% of energy capture
  - Modern HAWTs operate well below this
- Root loss (≈5%)
  - Inner 25% of rotor …
  - … designed for structural integrity
  - → *Poor root aerodynamics*
- Wake loss (≈8−40%)
  - Not operating in isolation





Novel Turbine Concept

- Dual Rotor Wind Turbine (DRWT)
  - Add a secondary, co-axial rotor
  - Rotors rotate independently
  - Co- or counter rotating
- Aims:
  - Reduce root loss
  - Reduce wake loss
    - Enhance wake mixing
- Secondary rotor inversely designed using BEM
  - Betz optimal rotor
- Analyzed design using RANS and LES



Dual rotor wind turbine (DRWT) concept

Lab models (courtesy Dr. Hui Hu)

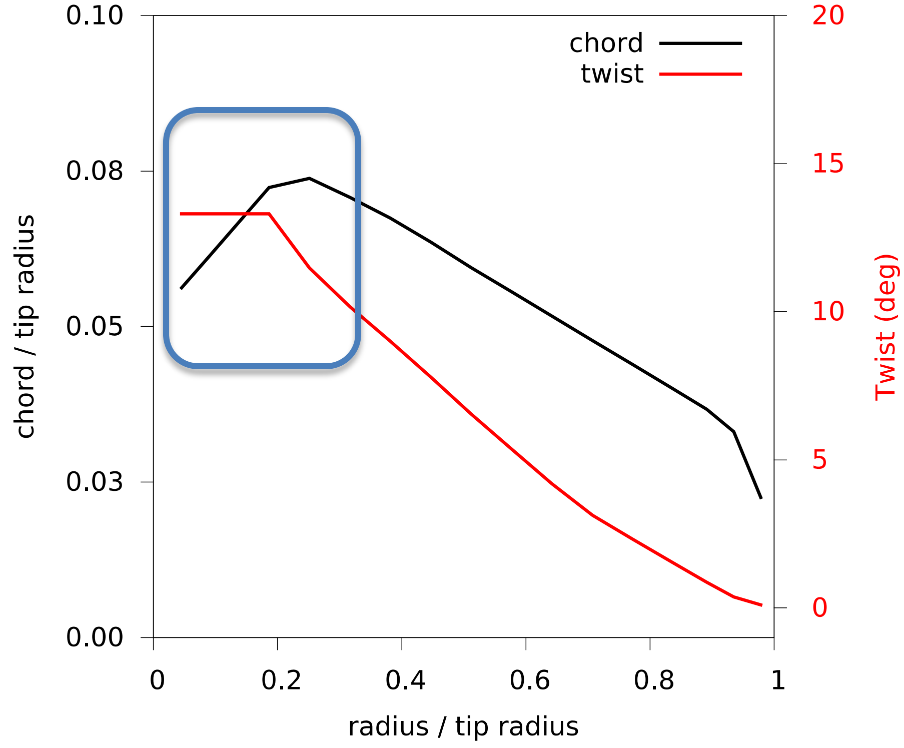
DUAL ROTOR DESIGN

Primary Rotor – NREL 5 MW offshore

- Conceptual design
  - $D = 126.0\ \text{m}$

- Constraints:
  - Transportation (chord)
  - Manufacturability (twist)
  - Loads (thickness)

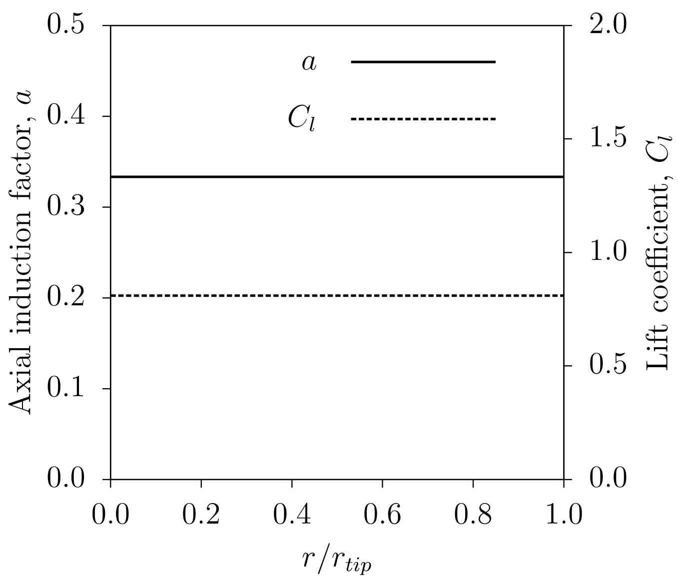
→ **Aero losses**



Applies to all utility-scale HAWTs

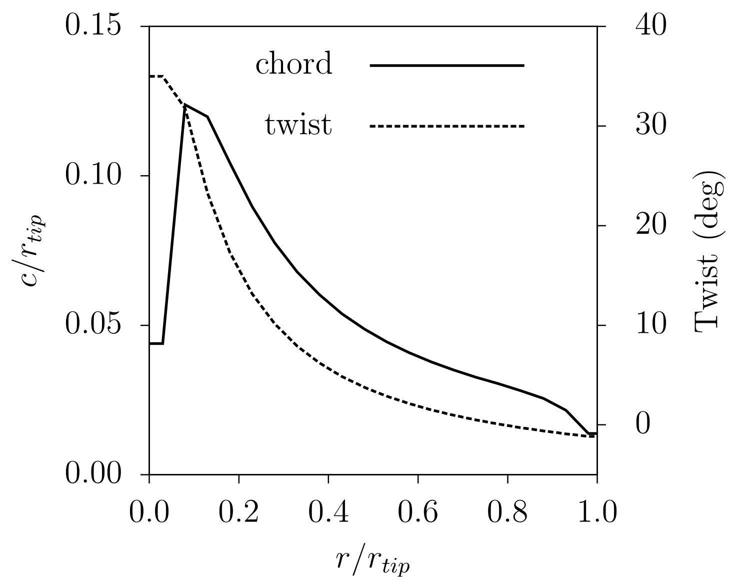
Secondary Rotor Design

Input



- DU 96 airfoil
- Betz optimum rotor
  - $a = 1/3$

Output



- Chord distribution
- Twist distribution
- Non-dimensional

NUMERICAL METHODS

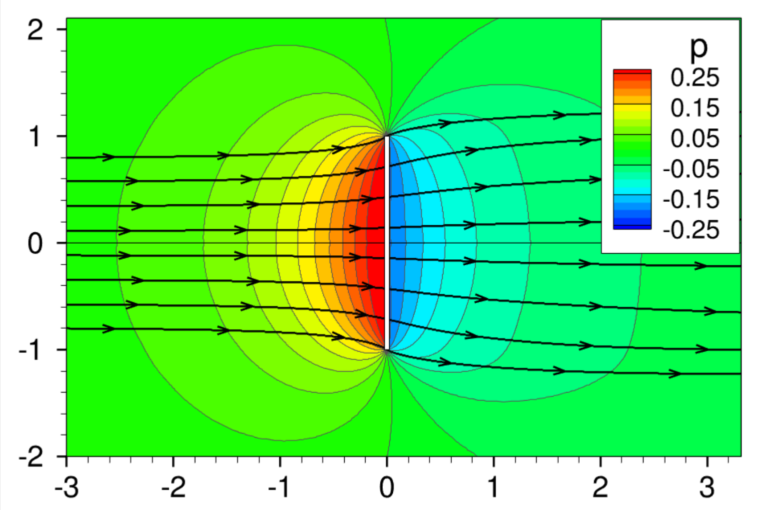
1. **RANS + Actuator Disk**
2. LES + Actuator Line

CFD: RANS + Actuator Disk

- *Selvaraj,* 2014 (M.S. thesis)
- Reynold's Averaged Navier-Stokes + Actuator Disk
  - Incompressible flow
- Axisymmetric computations
- Implemented in OpenFOAM (SimpleFOAM)

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

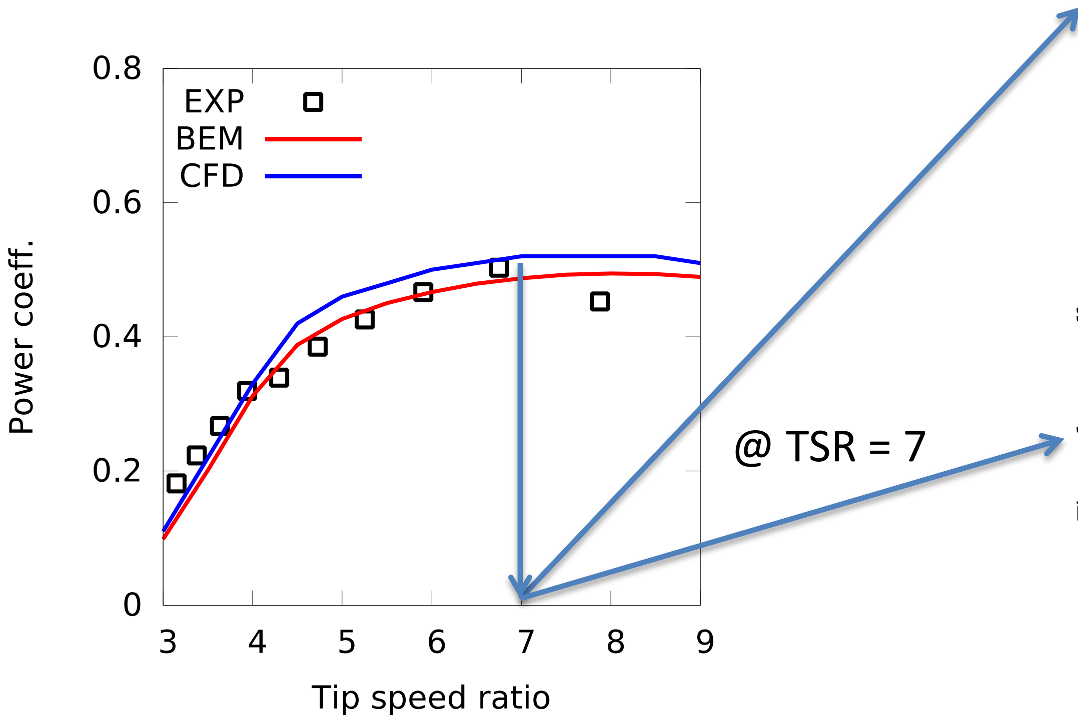
$$\bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial {x_j}^2} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j} + \boxed{\frac{f_i}{\rho}}$$

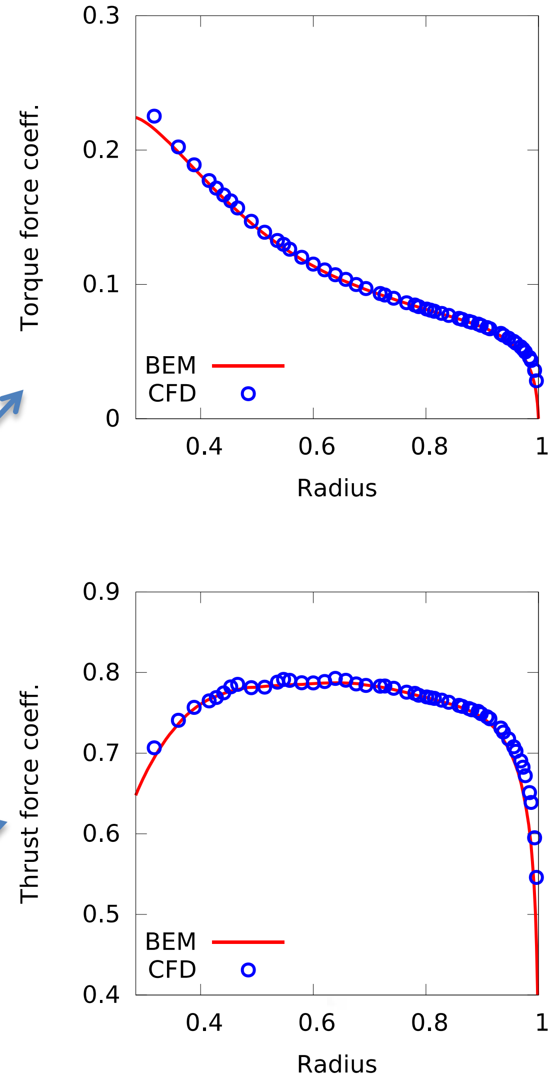


CFD Validation: Single Rotor HAWTs

Risø Turbine:

- Conventional, single-rotor design
- 100 kW
- Fixed Pitch, Stall Regulated
- $D = 19.0 \text{ m}$

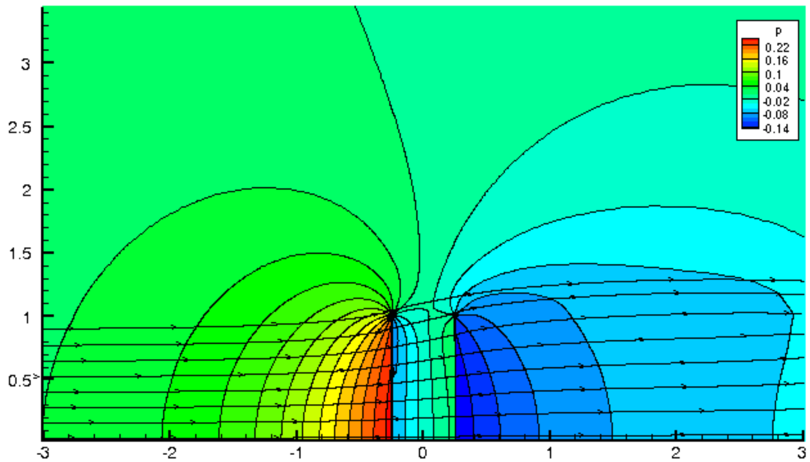


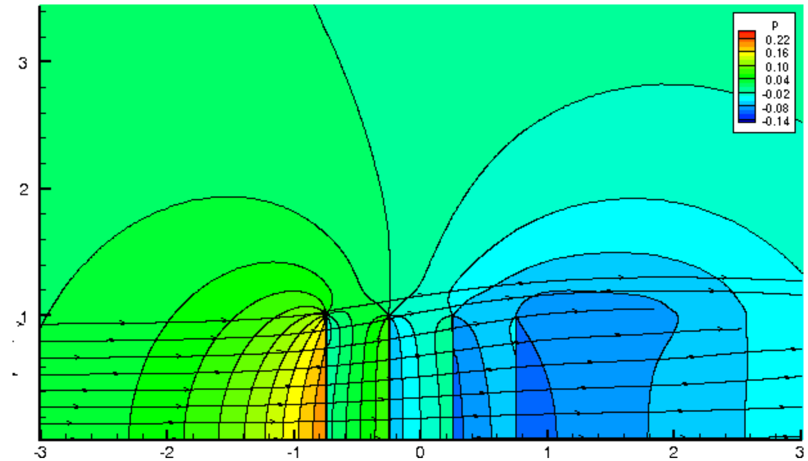


Multiple Actuator Disk Validation

- *Newman (1985)** extended 1-D theory to multiple disks
- Equal-size, uniformly-loaded disks in tandem

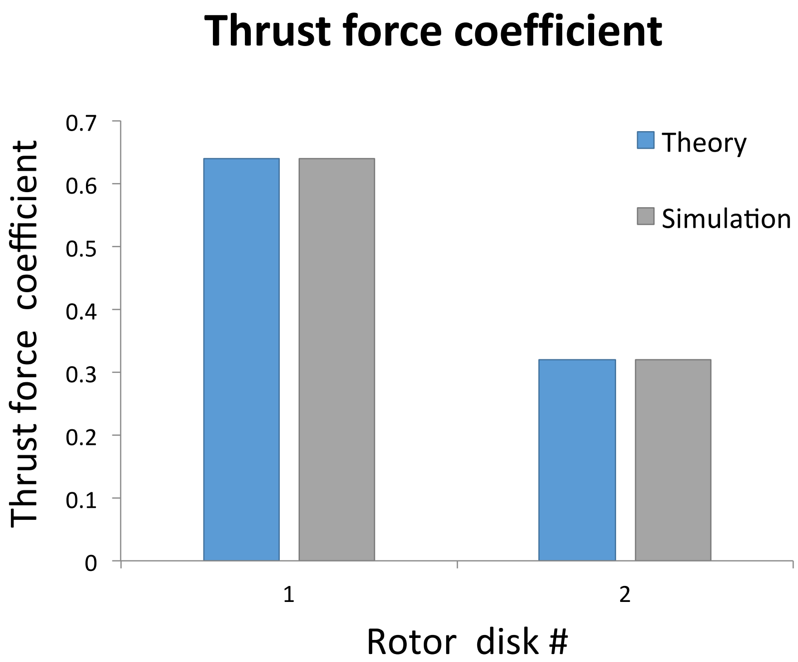
- Validate against analytical solutions for 2, 3, & 4 disks
- Specify C_T, compute C_T and C_P

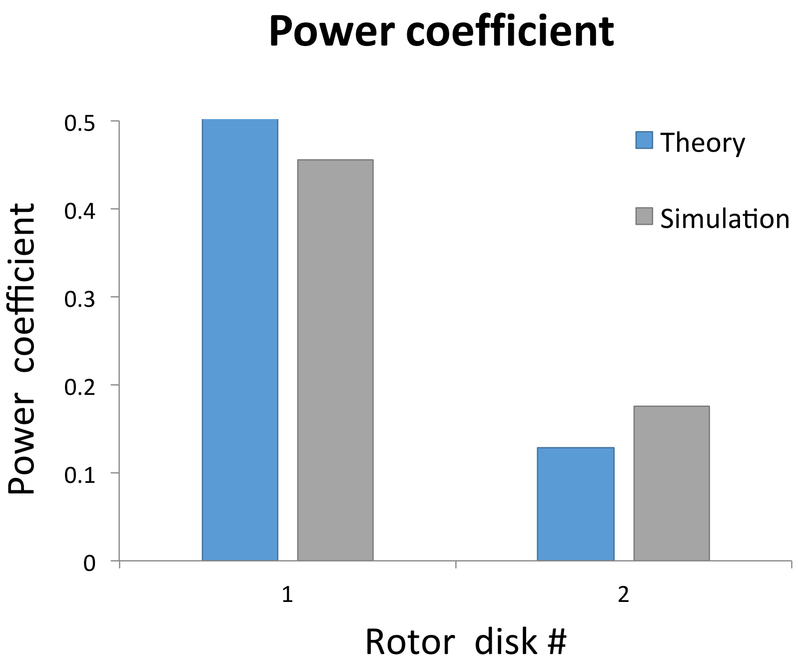




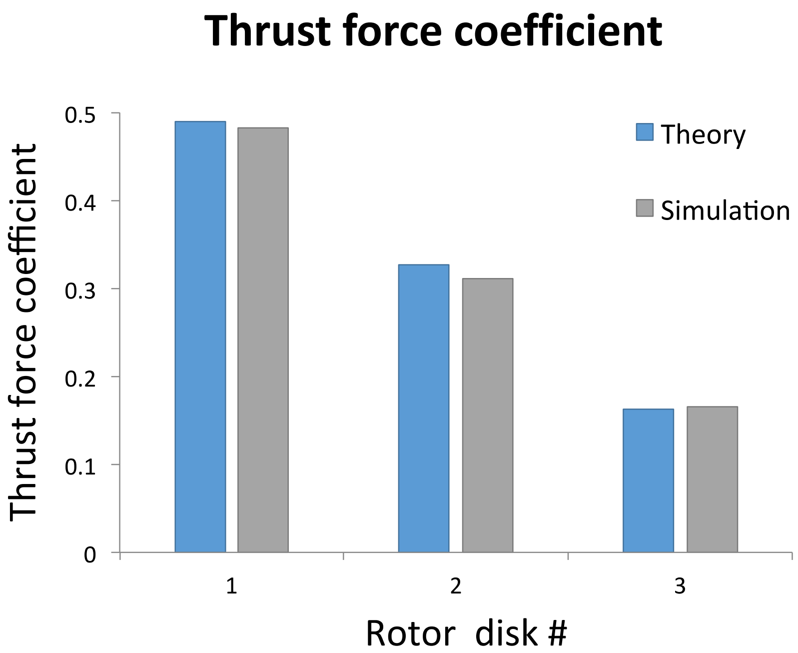
*Newman, B 1986 *Journal of Wind Engineering and Industrial Aerodynamics* **24** pp. 215–225

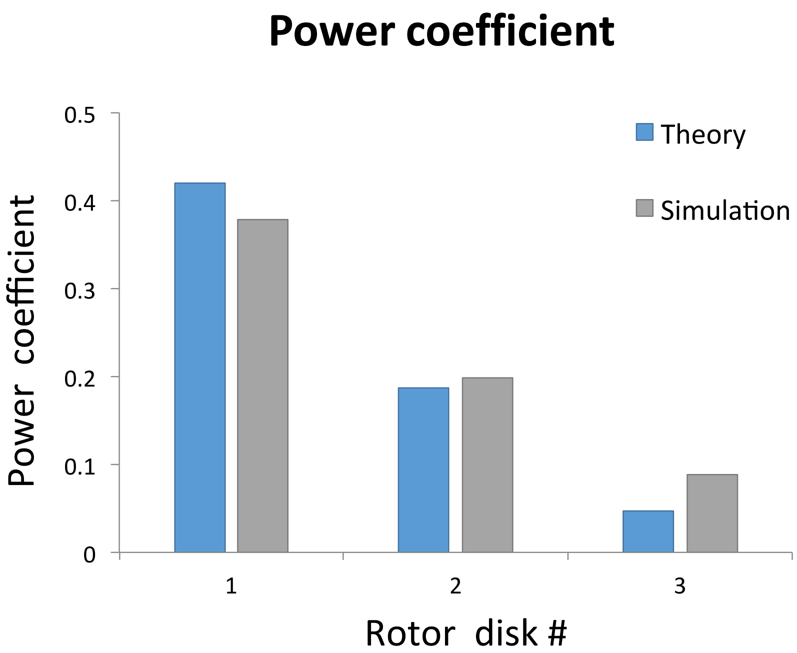
RANS Validation: Two Disks



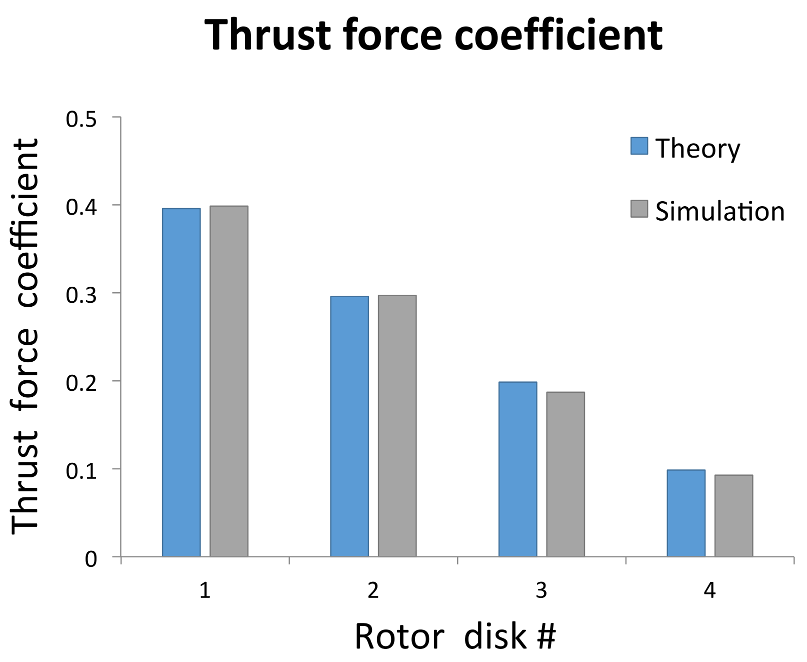


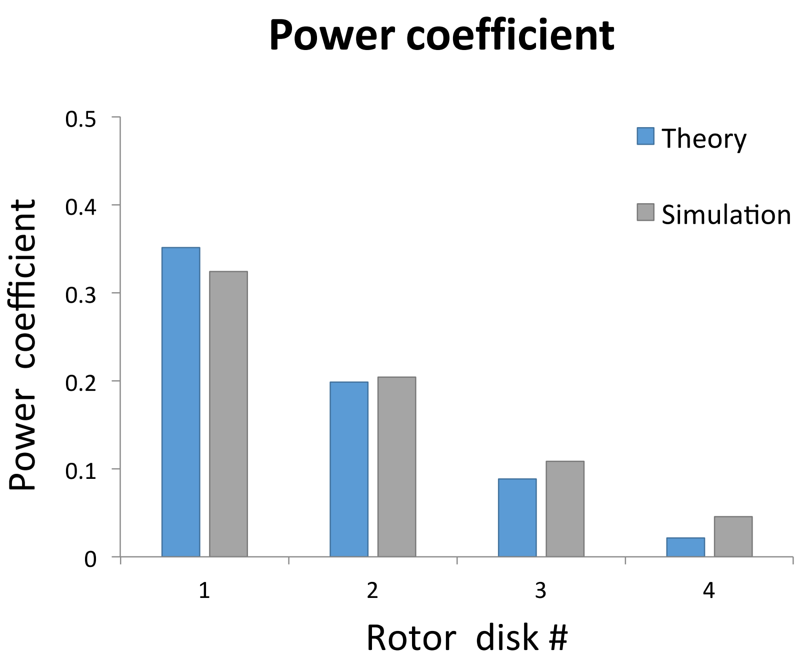
RANS Validation: Three Disks





RANS Validation: Four Disks





Optimization Study (RANS)

- Optimum Betz rotor design for secondary rotor ignores rotor-rotor interaction effects → not optimum for DRWT use

- Optimize secondary rotor for DRWT performance
  - Still isolated turbine … not wind plant

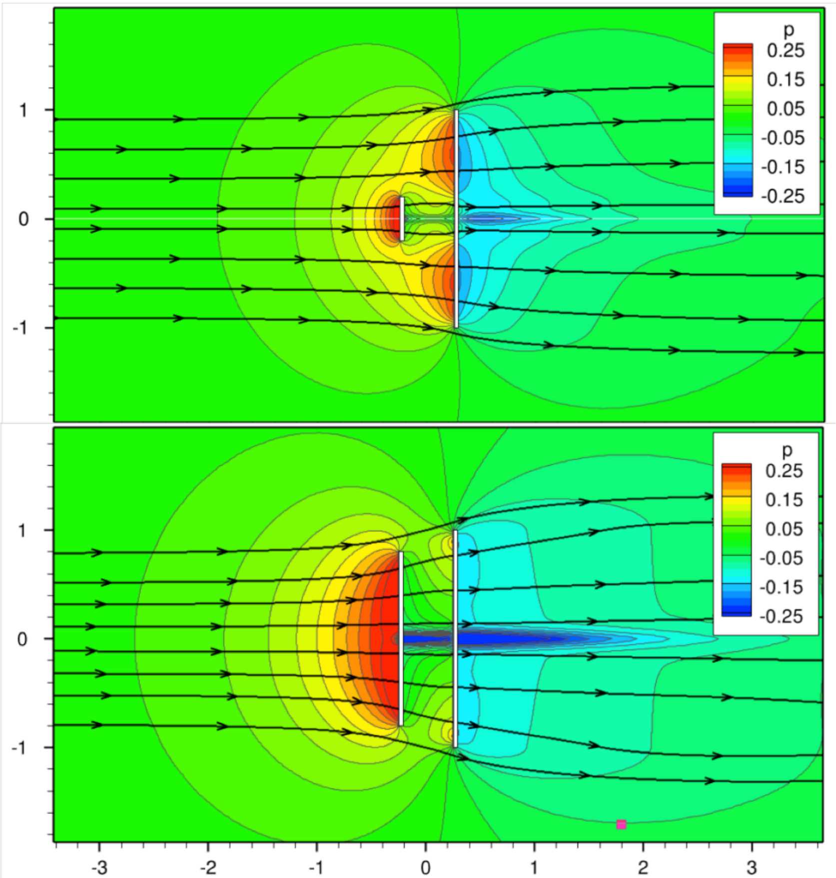
- Parametric sweeps; vary:
  - #1: Secondary rotor size & TSR

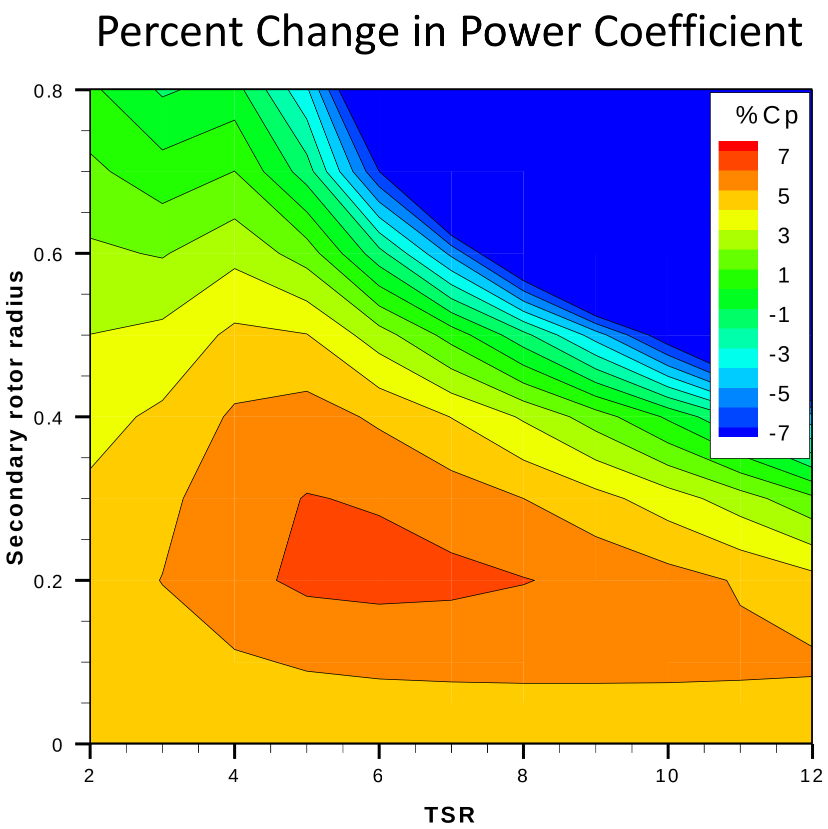
    Hold rotor-rotor separation: $\Delta x = 0.5 \times r_{t_{main}}$

  - #2: Rotor-rotor separation & TSR

    Hold secondary rotor size: $r_{t_{secondary}} = 0.3 \times r_{t_{main}}$

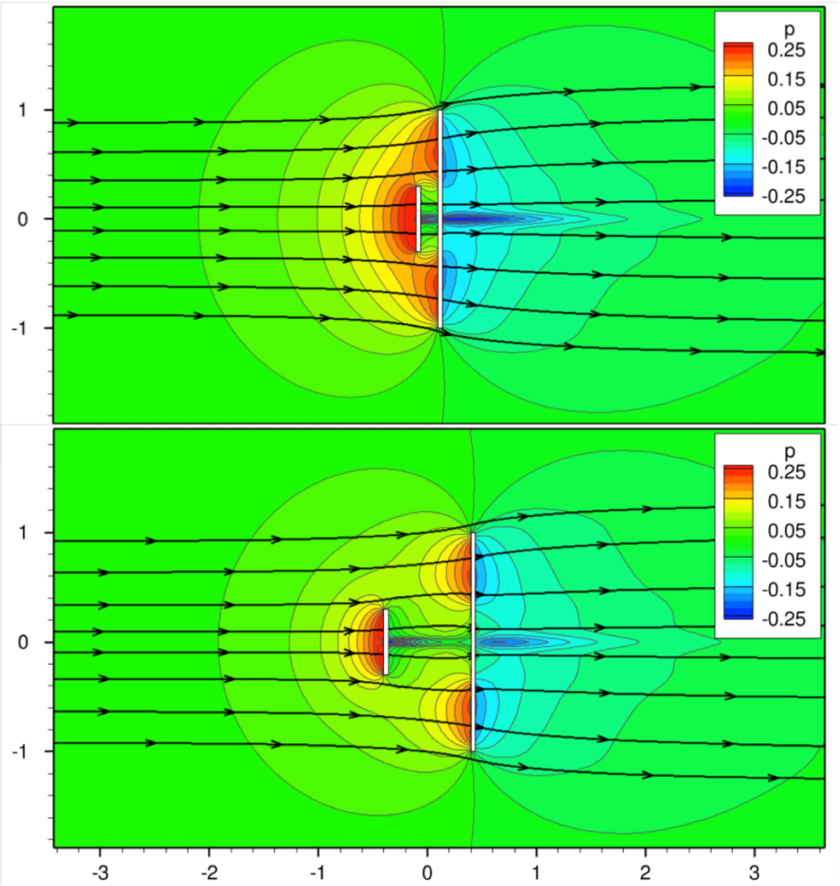
Size of the secondary rotor varied

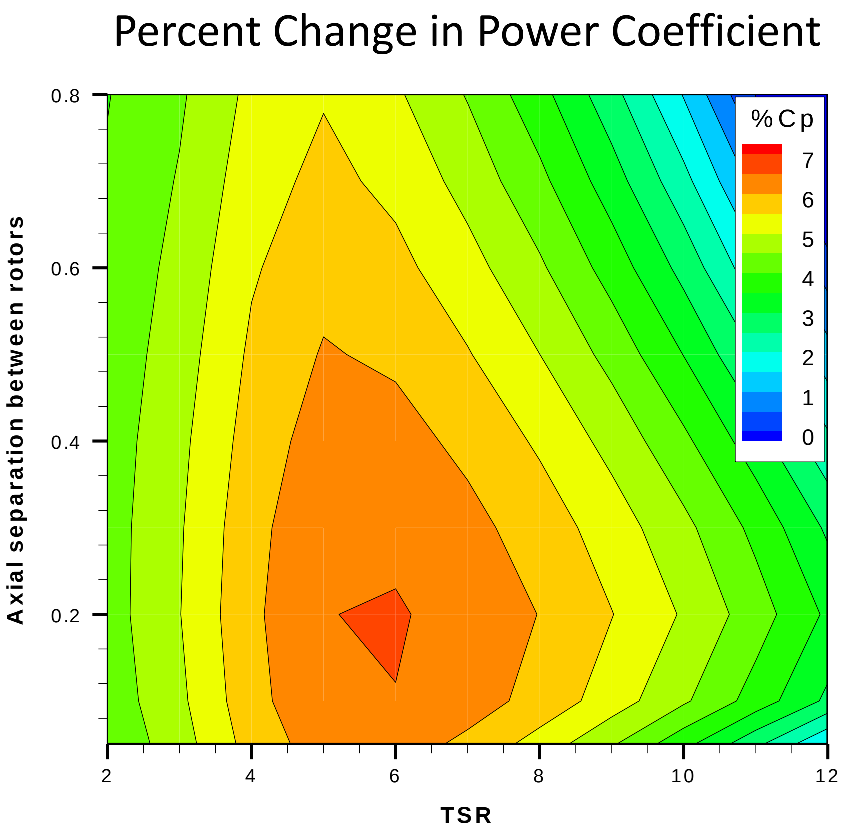




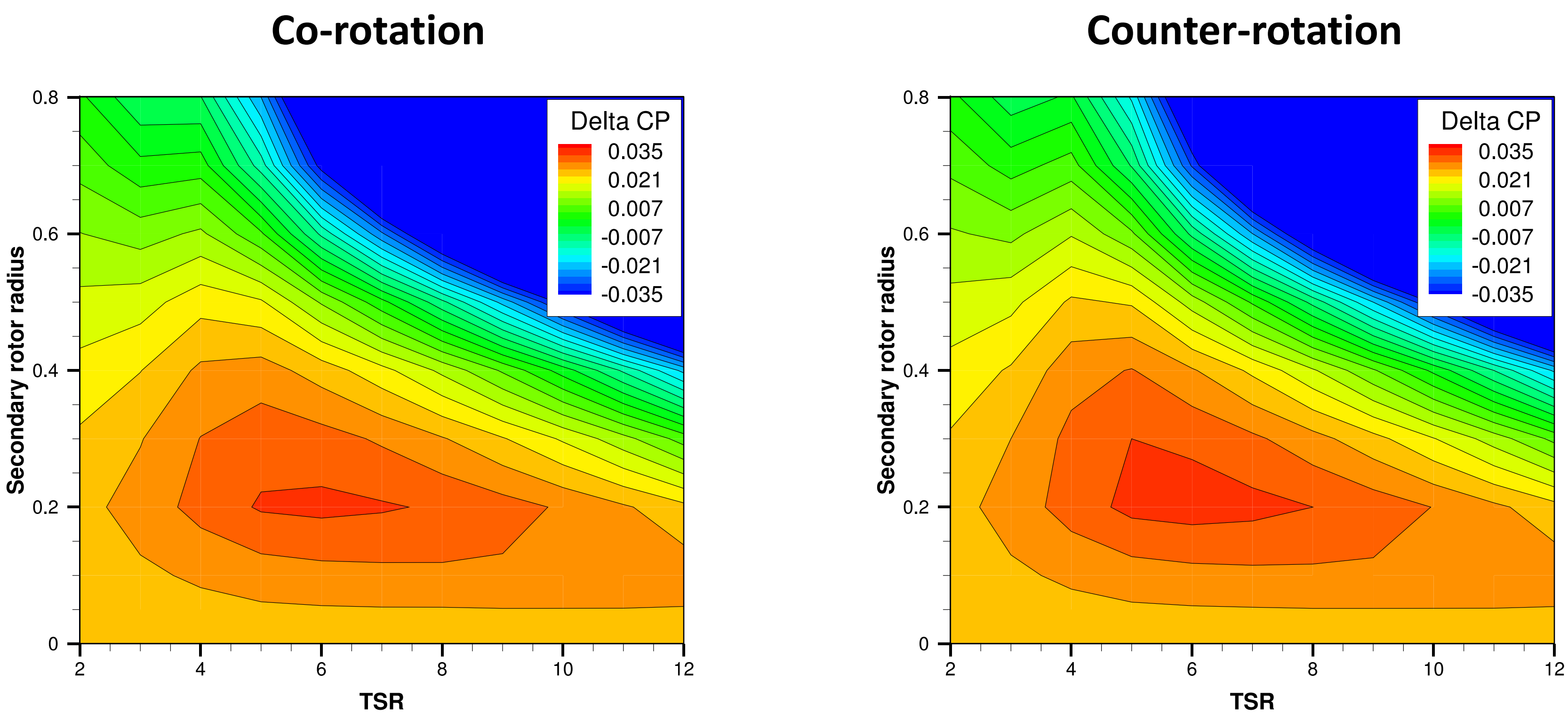
Rotor Spacing

Axial spacing between primary & secondary rotors varied





Co- Versus Counter-Rotation



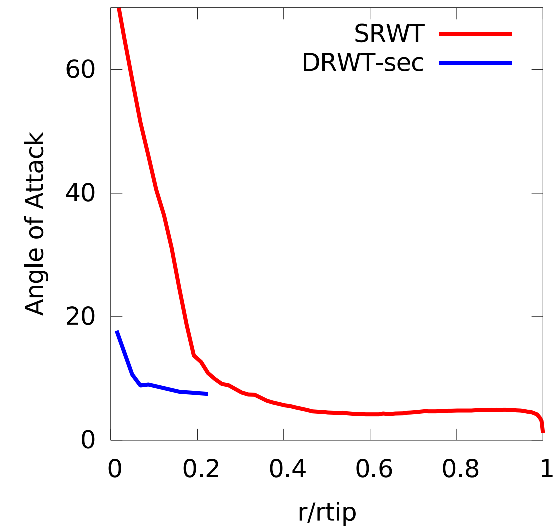
- Little influence of rotation direction
- Counter-rotation gives slightly better performance

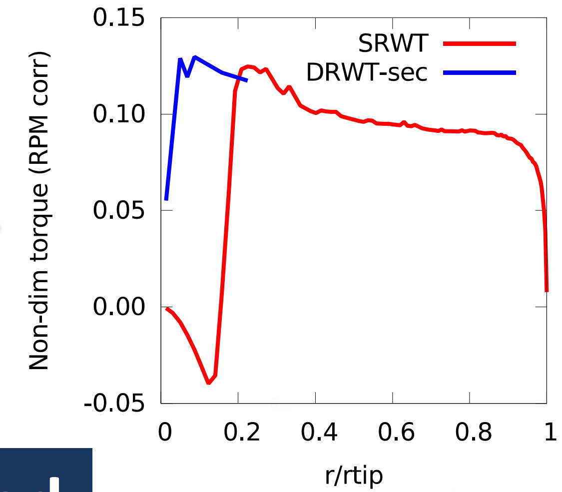
Optimization Study

Results:

- Secondary rotor:
  - Optimal size:
    $$r_{t_{secondary}} = 0.3 \times r_{t_{main}}$$
  - Optimal spacing:
    $$\Delta x = 0.2 r_{tip}$$
  - Optimal TSR = 6

- DRWT design:
  - Reasonable AoA
  - Efficient torque (power) generation in root region





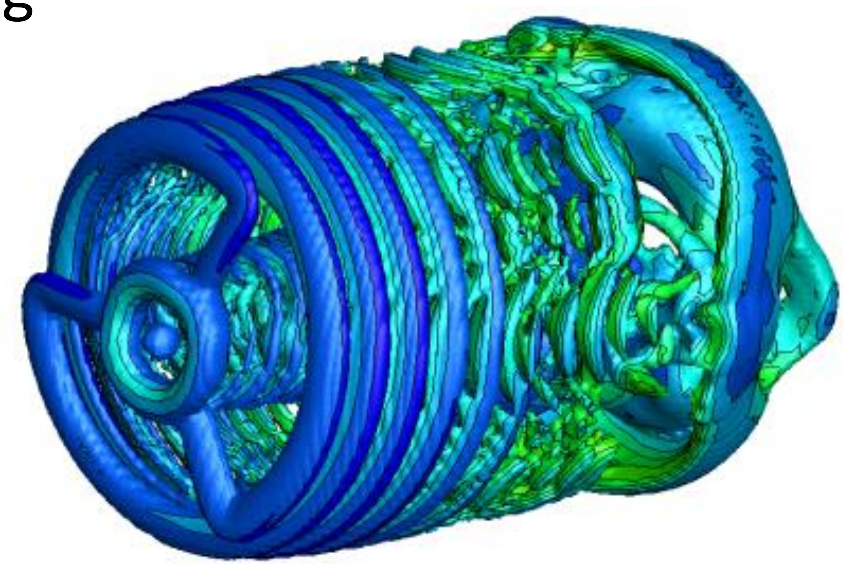
7% increase in C_p observed

NUMERICAL METHODS

1. RANS + Actuator Disk
2. **LES + Actuator Line**

Large Eddy Simulations

- Motivation
  - Analyze wake mixing
  - Unsteady features
  - Unsteady loading
- RANS optimized DRWT config
  - Counter-rotating
- Compare with SRWT
- SOWFA
  - LES + Actuator Line
  - SGS model: Smagorinsky



LES + Actuator Line

- Governing eqs.: unsteady, incompressible N-S

- Spatially filtering → resolve variable denoted by (~)

$$\frac{\partial \widetilde{u}_i}{\partial x_i} = 0,$$

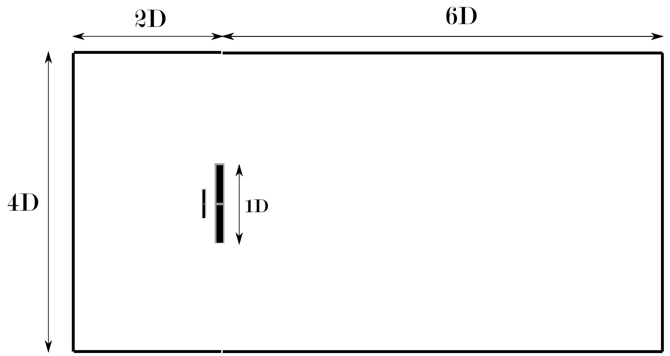
$$\frac{\partial \widetilde{u}_i}{\partial t} + \widetilde{u}_j \left(\frac{\partial \widetilde{u}_i}{\partial x_j} - \frac{\partial \widetilde{u}_j}{\partial x_i} \right) = -\frac{\partial \widetilde{p^*}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \nu \frac{\partial^2 \widetilde{u}_i}{\partial x_j^2} - \underbrace{f_i/\rho_0}_{\text{turbine force}}$$

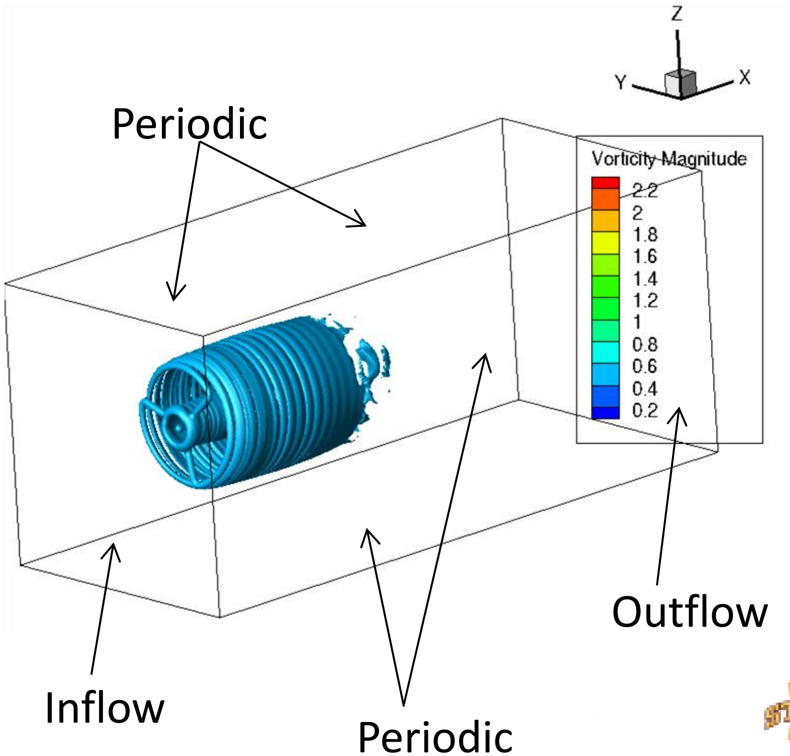
- Assumptions:
  - Neutral atmosphere → buoyancy ignored
  - Small domain → Coriolis plays little role
  - Zero inflow & background turbulence
  - Turbines represented w/ body forces (Actuator line)

DRWT LES

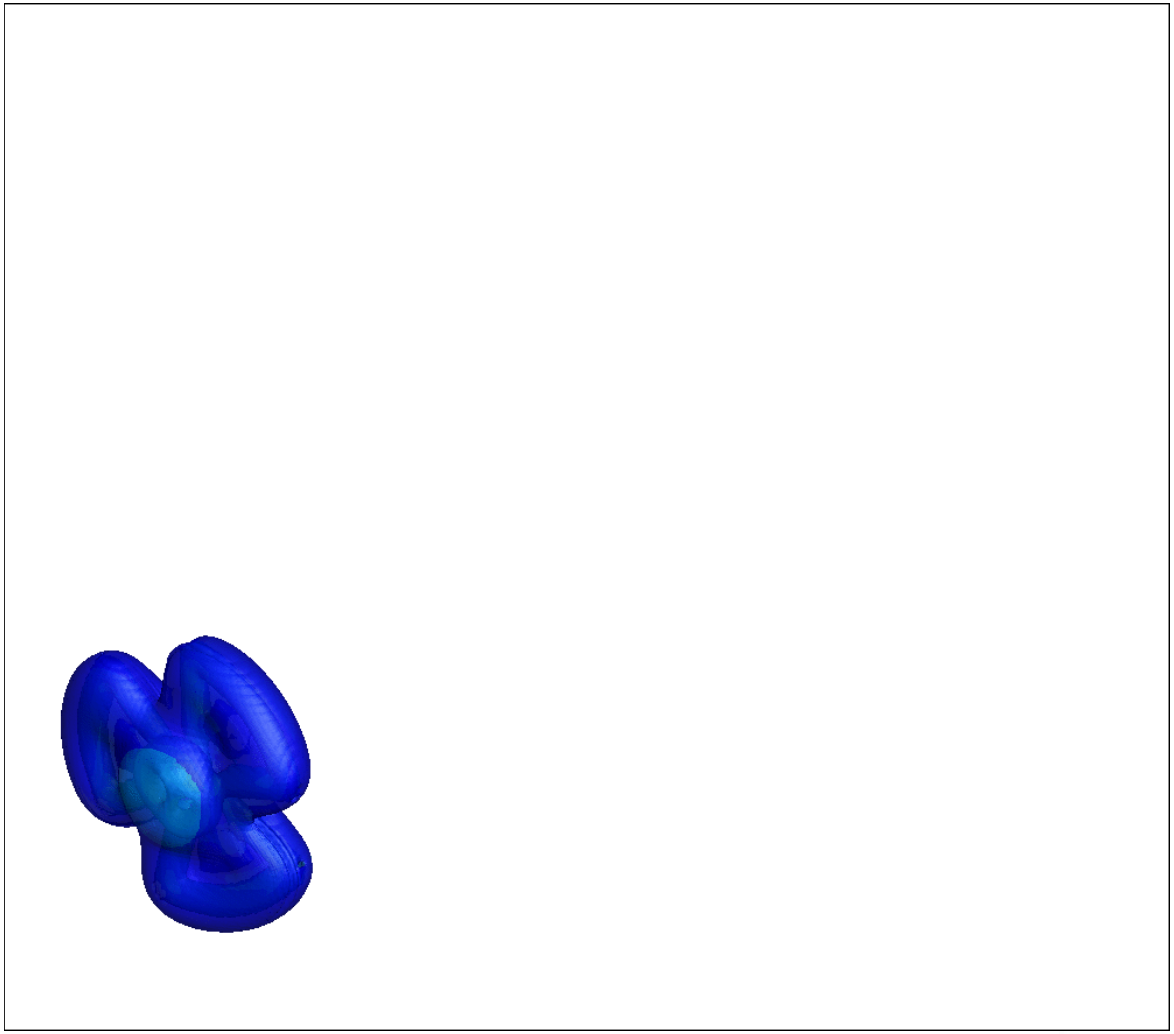
- Simulated 200 sec
  - Averaged from 150 – 200 s for performance comparisons
- U_∞= 8 m/s
- Periodic BCs (side & top):
  - Infinite array in cross stream dir…

  … but large separation → isolated
- Nacelle & tower ignored
- Uniform flow, no turb, no buoyancy, no Coriolis
- 1 simulation ~ 6K core hours (~24 hrs on 256 cores)



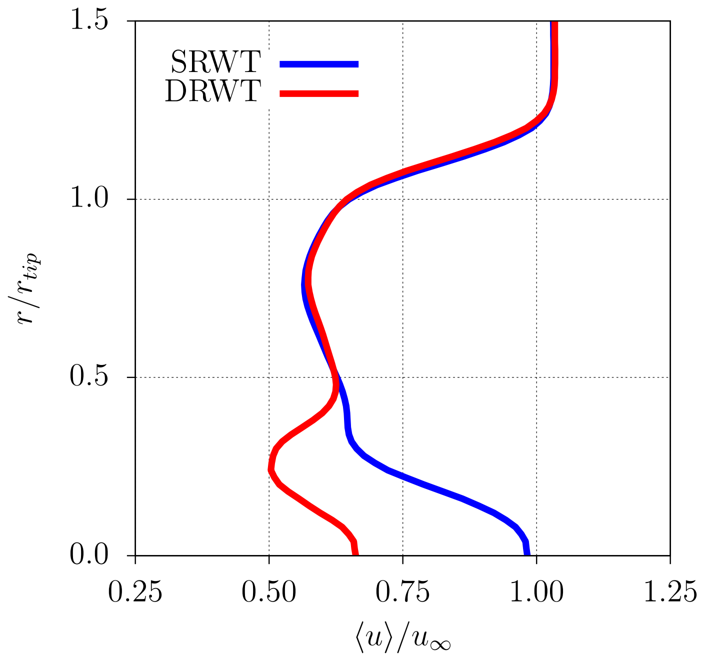


DRWT LES

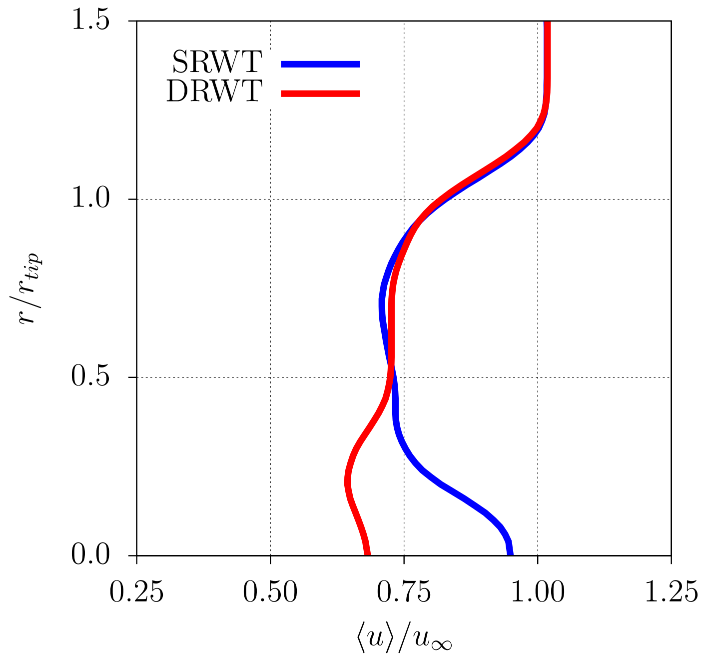


~5% increase in C_P observed

DRWT LES Results: Wake Evolution



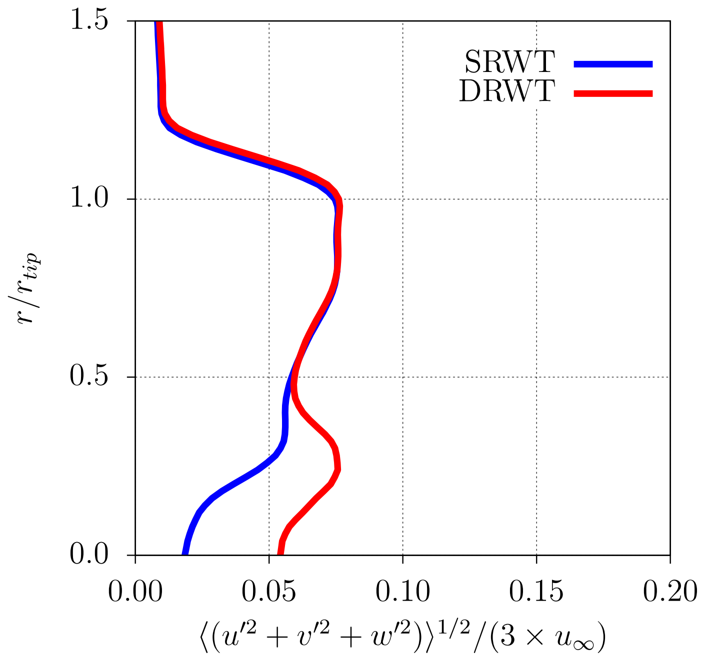
X = 2D



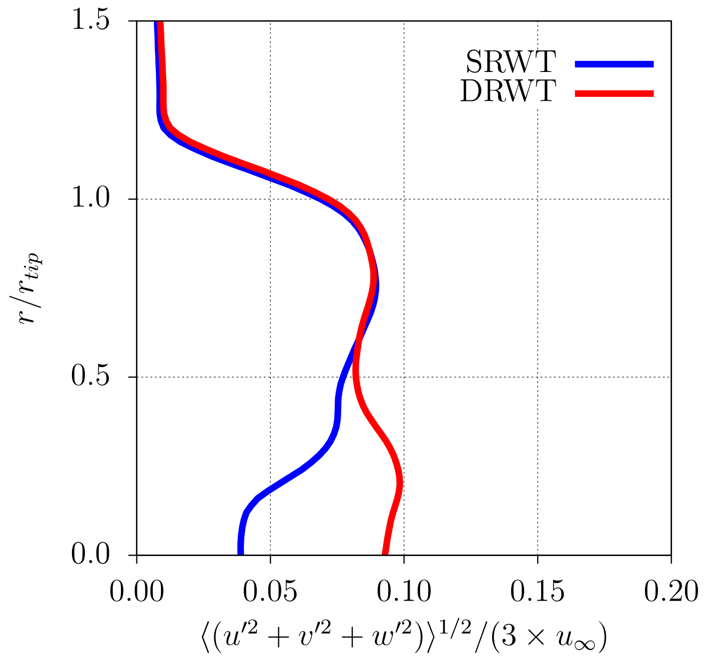
X = 4D

- Secondary rotor extracting energy → higher deficit near root
- Insignificant difference in wake deficit near tip

DRWT LES Results: Wake Evolution



X = 2D



X = 4D

- Root: higher turbulence intensity
- Tip: Insignificant difference

Absence of background turbulence, ABL, tower → wake /vortex systems of the 2 rotors not interacting

Conclusions

- Designed a DRWT using inverse BEM
- Validated RANS + Actuator disk
  - Single and multi-rotor turbines
- Optimized DRWT using RANS + AD
- Performance analysis using LES
  - C_P increase of ~5% (RANS: 7%)

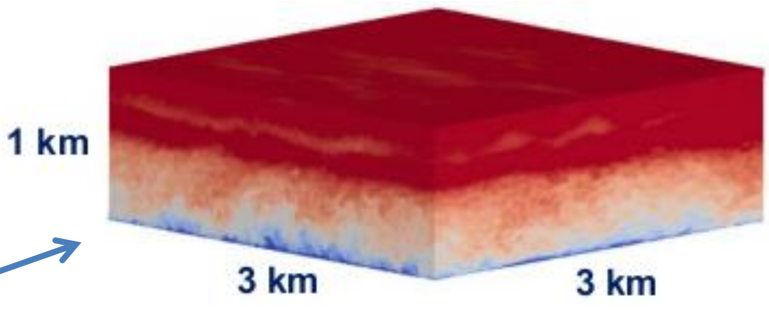
FUTURE WORK

Future Work

1. ABL Simulations
2. Wind Farm Simulations
3. Enhance Wake Mixing
4. Acoustic Study
5. Cost Analysis
6. Experimental Validation

Atmospheric Boundary Layer Simulations

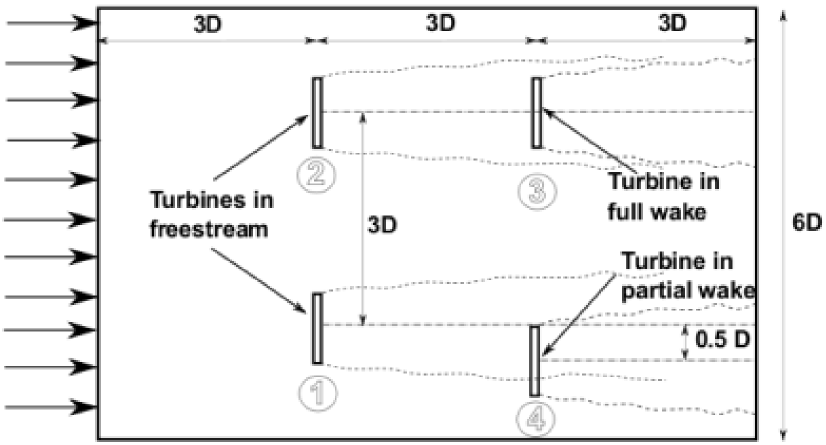
- Uniform inflow is not realistic
- What are the effects of a fully turbulent ABL?
  - Power Production
  - Acoustics
  - Stochastic Loading
- SOWFA Precursor ABL
  - Wall model for ground
  - Potential temperature profile
    - Unstable vs Neutral vs Stable



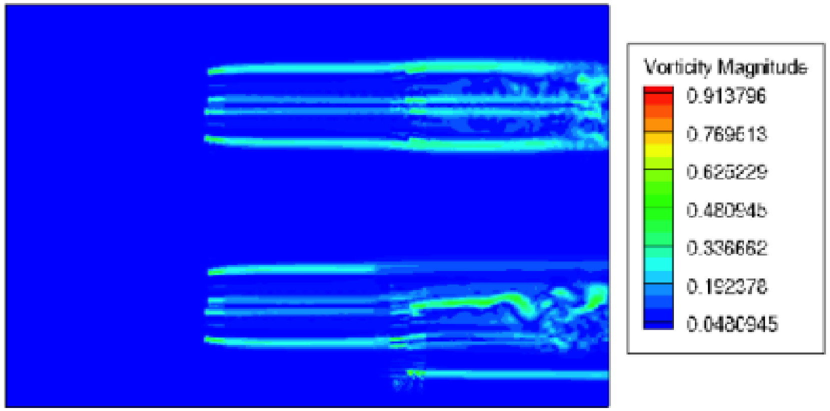
From SOWFA webinar

Wind Farm Simulations

- DRWT vs SRWT
  - Do DRWT arrays act more efficiently?
- Full vs partial wake effects
- Fully turbulent ABL
  - Coriolis & buoyancy included

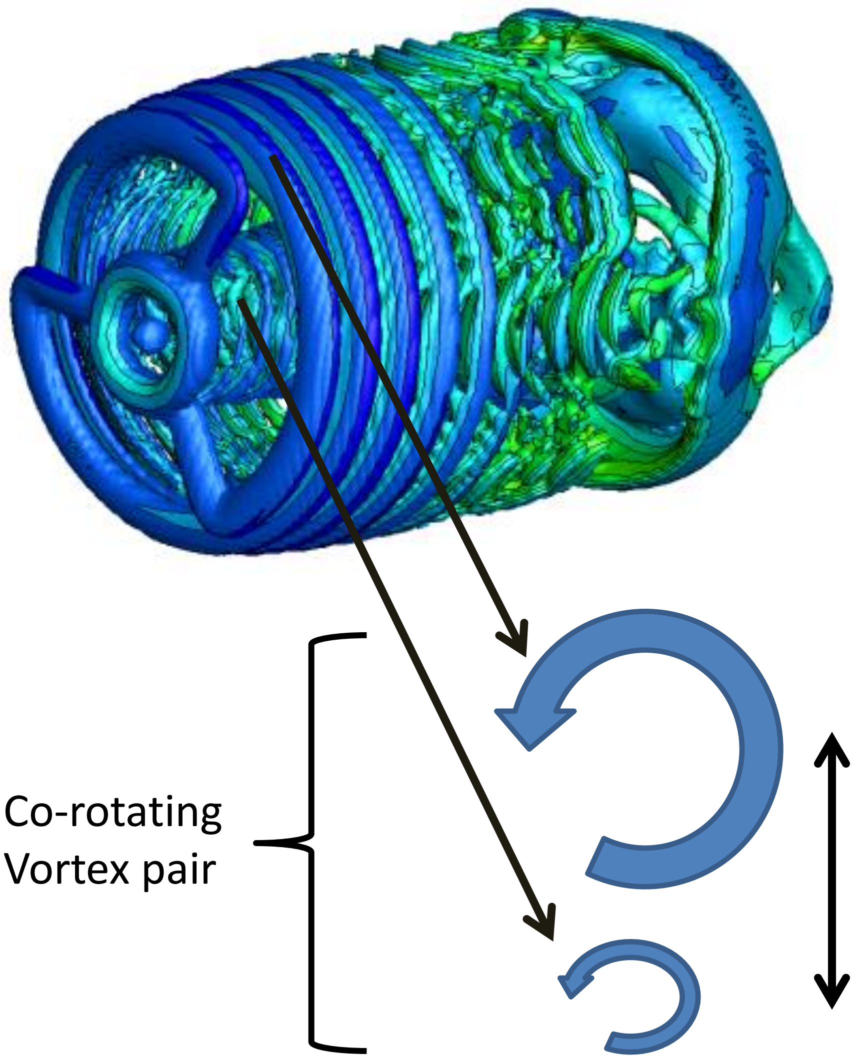


(a) Wind plant layout



(b) Vorticity magnitude

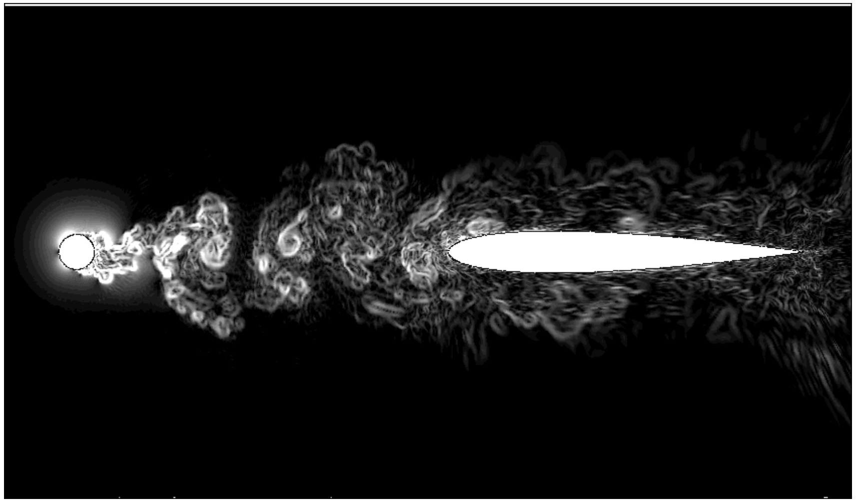
Enhance Wake Mixing



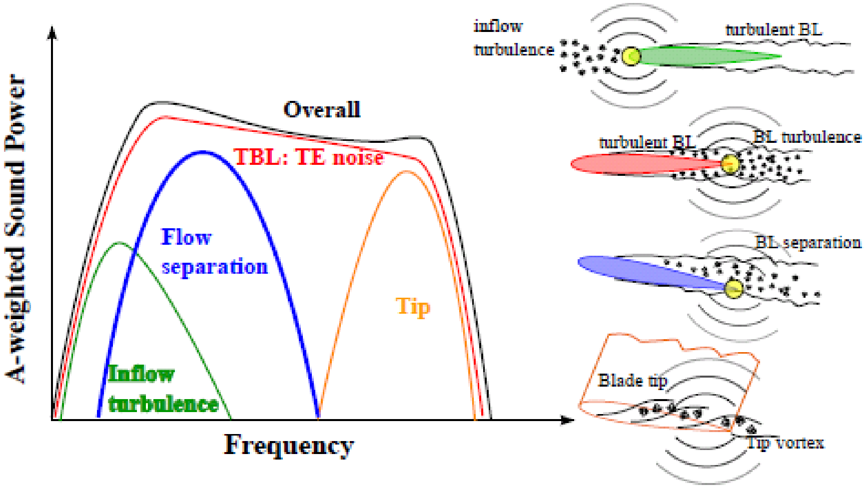
- Wake Loss > Root Loss
- Instigate excitation of vortex-pair instability
- Re-energize wake
- Wake Control
  - Secondary blade size/design?
  - Control Algorithm?
    - $\theta, \lambda_{1,2} = f\left(U_{\infty}, \frac{\partial \theta_t}{\partial z}, ?\right)$

Acoustic Study

- *Airfoil-Rod* interaction
  - Leading edge noise from primary rotor
    - Thin airfoil of secondary rotor
    - Thick root section of primary rotor
- Potential Field
  - Trailing edge noise from secondary rotor
- Semi-analytical models
  - *Sears (1941)*
  - Cascade Response
- **A lot to learn here!**



Courtesy Bharat Agrawal



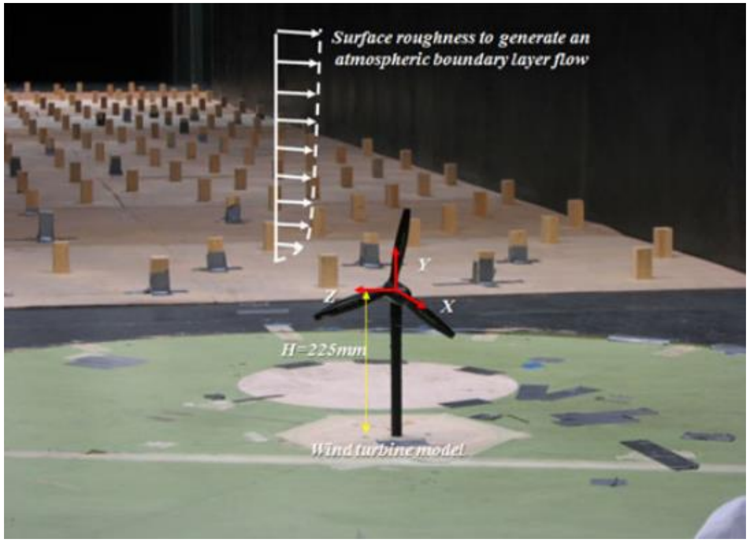
Cost Analysis

- *Wind Turbine Design Cost and Scaling Model (2006)*
  - Calculates LCOE
  - Function of turbine size
- Extended to DRWT
  - Refine analysis
- Drivetrain Costs?
  - Collaborate w/ industry

	SRWT	DRWT
Onshore	$0.0464/kWh	$0.0438/kWh
Offshore	$0.0807/kWh	$0.0767/kWh

Experimental Validation

- Validate CFD results w/ Dr. Hu's research group
  - Replicate previous wind tunnel experiments
- AABL + Model Turbines
  - Fabricate DRWT models
- Isolated and Array



From *Hu et al. (2012)*

QUESTIONS?