National Rotor Testbed Overview for DOE Science Panel

SAND2017-4446PE

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26th April 2017

U.S. DEPARTMENT OF ENERGY

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NRT Design Motivation

- Platform to conduct experiments with wind turbine wakes
- Generate wakes with same initial conditions as GE 1.5sle
- Provide high quality data for V&V of models

Aerodynamic Objective

- Create same initial conditions of velocity/momentum deficit at rotor plane as fullscale machine (GE 1.5sle)
- $\Gamma'\left(\frac{r}{R}\right)_{GE}$ is from FAST model
- Inverse design - solve for blade shape to produce scaled wake
- Objective functions

$$\Gamma'\left(\frac{r}{R}\right)_{NRT} = \Gamma'\left(\frac{r}{R}\right)_{GE}$$

$$C_l\left(\frac{r}{R}\right)_{NRT} = 0.6$$

NRT Functional Scaling Summary

✓ Designed to Scale (NRT = GE 1.5sle)

- $\Gamma'(\frac{r}{R})$ the spatial distribution of dimensionless, bound circulation to shed equal trailing circulation
- Equal $\Gamma'(\frac{r}{R})$ between scales also means equal induction and thrust coefficient ($a(\frac{r}{R})$ and C_T)
- Equal initial conditions for velocity field in wake (U/U_∞)
- Tip-speed-ratio, λ, for equal tip vortex spacing and parallel streamlines
- Consideration of inflow and location in ABL

✗ Not Designed to Scale

- Re_c, Re_D, L/D, C_P, geometry, aeroelasticity, above parameters outside Region 2

3D Printed Blade Mold at Oakridge

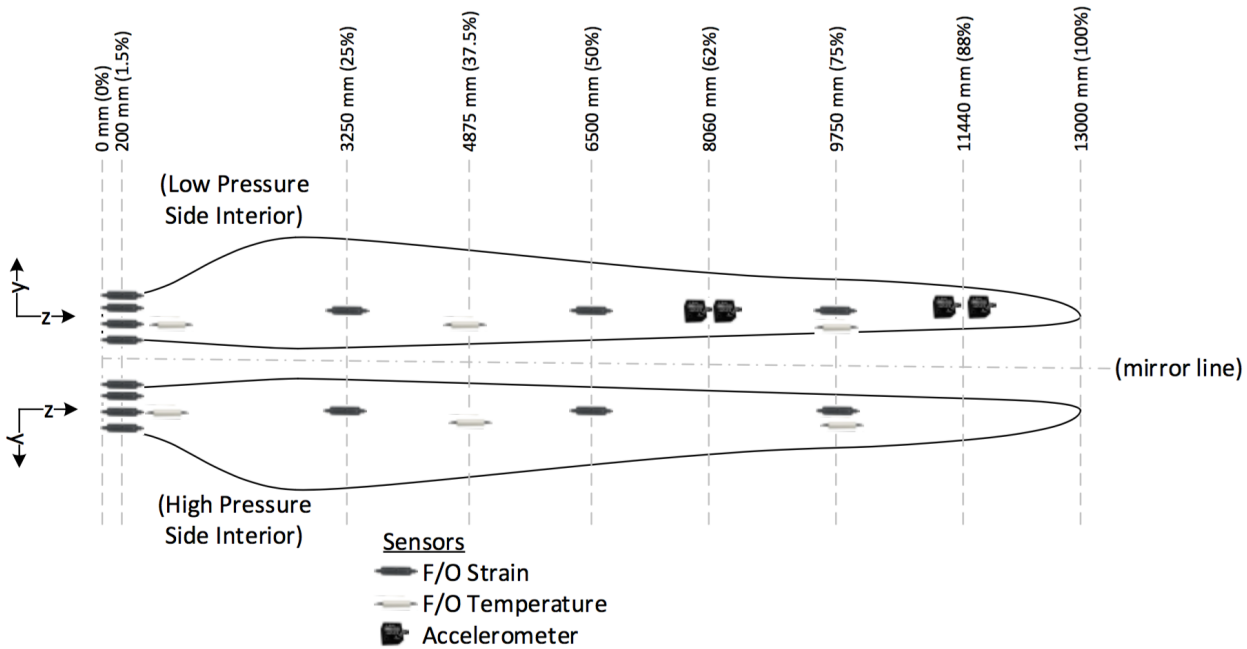
The ORNL Manufacturing Demonstration Facility Team next to a 3D printed wind turbine blade mold.

Blades Manufactured at TPI

Blades Manufactured at TPI

NRT Structural Instrumentation

Measurand	location %	Reason
flap strain ϵ_F	[0, 25, 50, 75]	load distribution
edge strain ϵ_E	[0]	root moment
acceleration a	[68, 82]	modal analysis
temperature T	[0, 38, 75]	thermal drift



Need for Additional Measurements

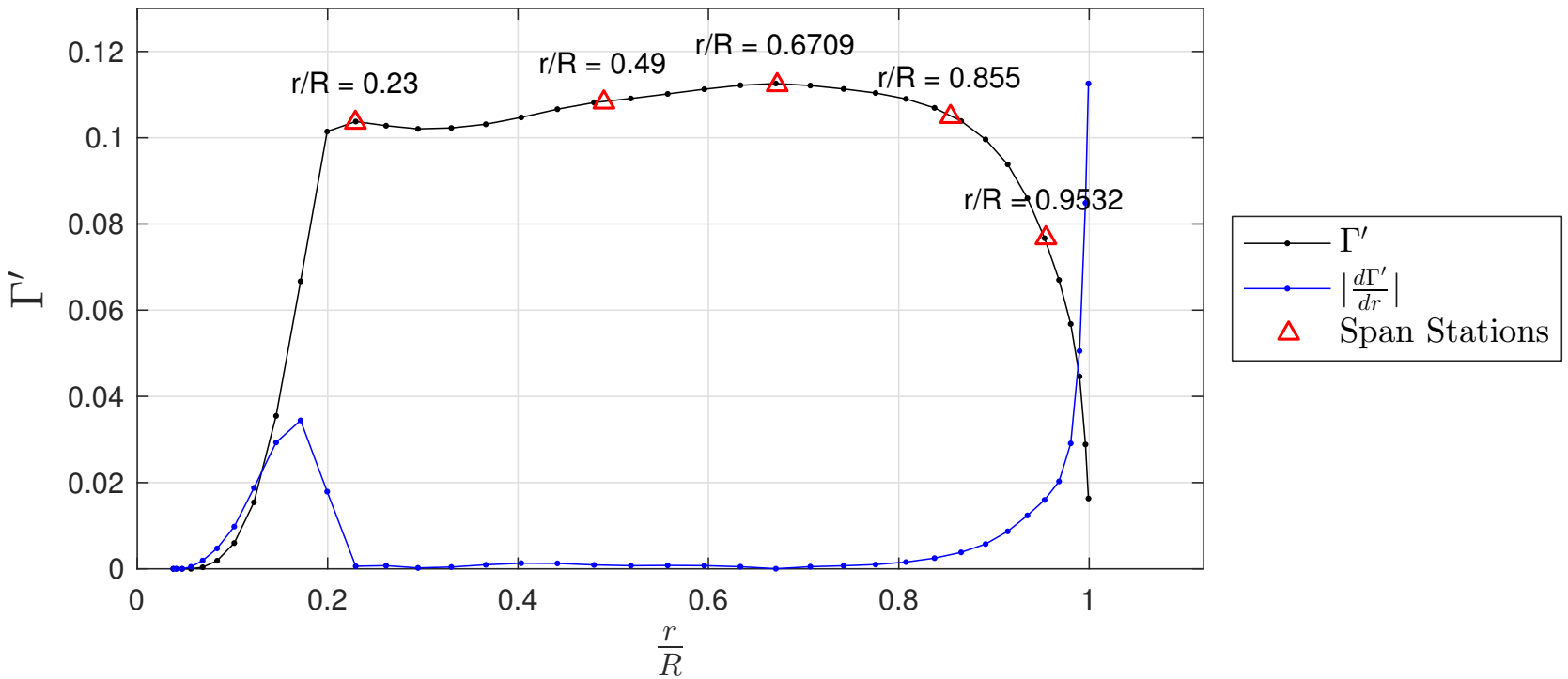
- Verify NRT design and validate models
  - Strain only provides integral loads
  - Verify circulation at discrete span stations
  - Wake/circulation agreement
  - Performance of airfoils on turbine versus wind tunnel design
  - Non-linear effects including dynamic stall, rotational augmentation, and boundary layer separation

Planned NRT Aerodynamic Instrumentation

Measurands	Possible Sensors	Importance
Blade induction $a_b(r/R)$	calculated	1
Circulation $\Gamma'(r/R)$	calculated	1
Flow Angle $\phi(r/R)$	5-hole pitot	1
Static Pressure $C_p(x/c, r/R, t)$, C_l, C_d	Pressure taps, piezoresistors, Fabry-Perot interferometer, Fiber Bragg Grating	1
Relative flow velocity $W(r/R)$	5-hole pitot, lidar	1
Boundary layer separation	Oil, tufts, hot film	2
Wake induction a	lidar	2
Tip loss factor f	calculated	2
Skin friction, transition	Oil, IR thermography, hot film, paint	3

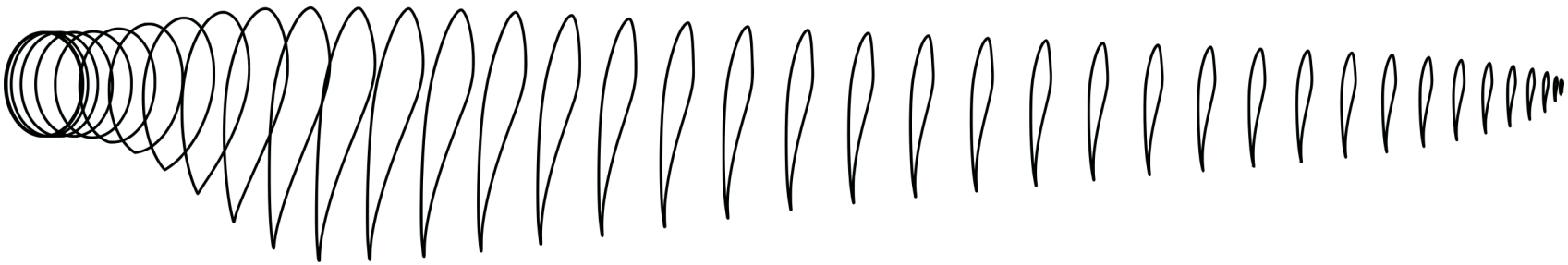
Aerodynamic Instrumentation Locations

- maximum chord and pure S814 at 0.23
- purely S825 outboard of 0.49
- maximum circulation, lift/span, and induction at 0.67 in R2
- maximum T/L and Q/L at 0.86
- minimum induction with tip losses at 0.95



NRT Conclusions

- NRT was designed to create a functionally scaled wake
- NRT is a highly instrumented blade
- NRT designed to meet validation requirements

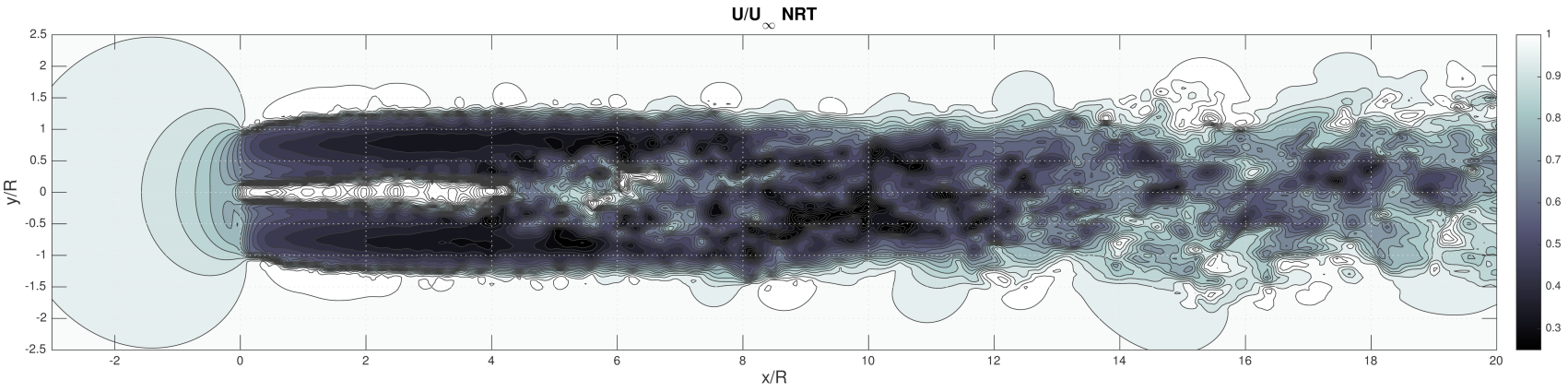


Questions for Panel

- Is there any additional instrumentation you would add?
- Which is a higher priority: verifying NRT performance or validating codes?

Extra Slides

A Scaled Wake

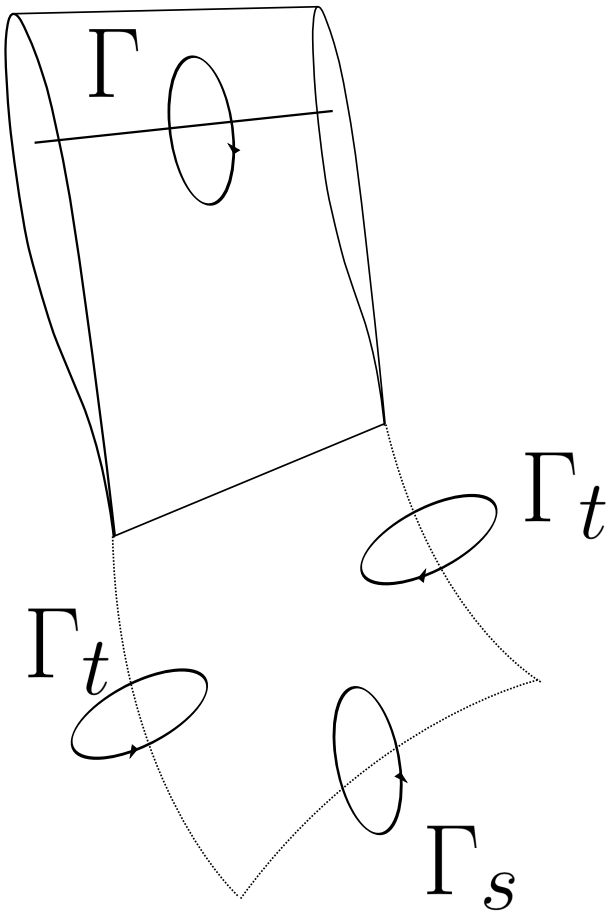


Create the same velocity field, $\frac{U}{U_\infty}$

How Is a Wake Created?

$$\Gamma'\left(\frac{r}{R}\right) = \frac{\Gamma(\frac{r}{R})}{RU_\infty} = \frac{C_l}{2}\frac{W}{U_\infty}\frac{c}{R}$$

- Circulation is proportional to lift
- Lift forces determine shed circulation
- Same as induction: $\Gamma' = 4\pi\frac{a(1-a)^2}{\lambda}$



Objective Function, Γ'_{fs}

- most common wind turbine in USA, GE 1.5sle, GE37c
- full-scale turbine model provided by manufacturer
- modeled in WT_Perf
- $\lambda = 9$
- smooth surface airfoil data from wind tunnel

Objective Function, C_l

- for a given circulation, C_l determines local solidity
- adequate stall margin
- efficient L/D
- smooth chord and twist distribution
- $C_l = 0.6$

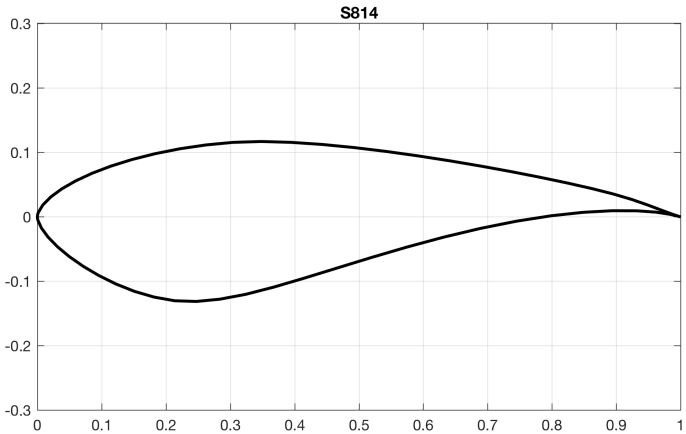
$$\Gamma'\left(\frac{r}{R}\right) = \frac{C_l}{2}\frac{W}{U_\infty}\frac{c}{R}$$

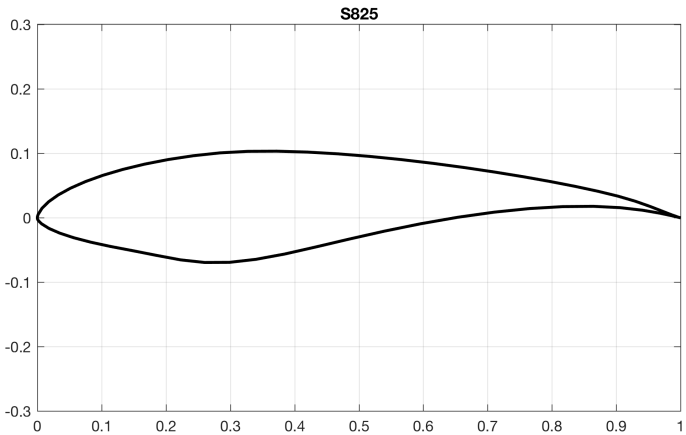
Airfoil Selection Criteria

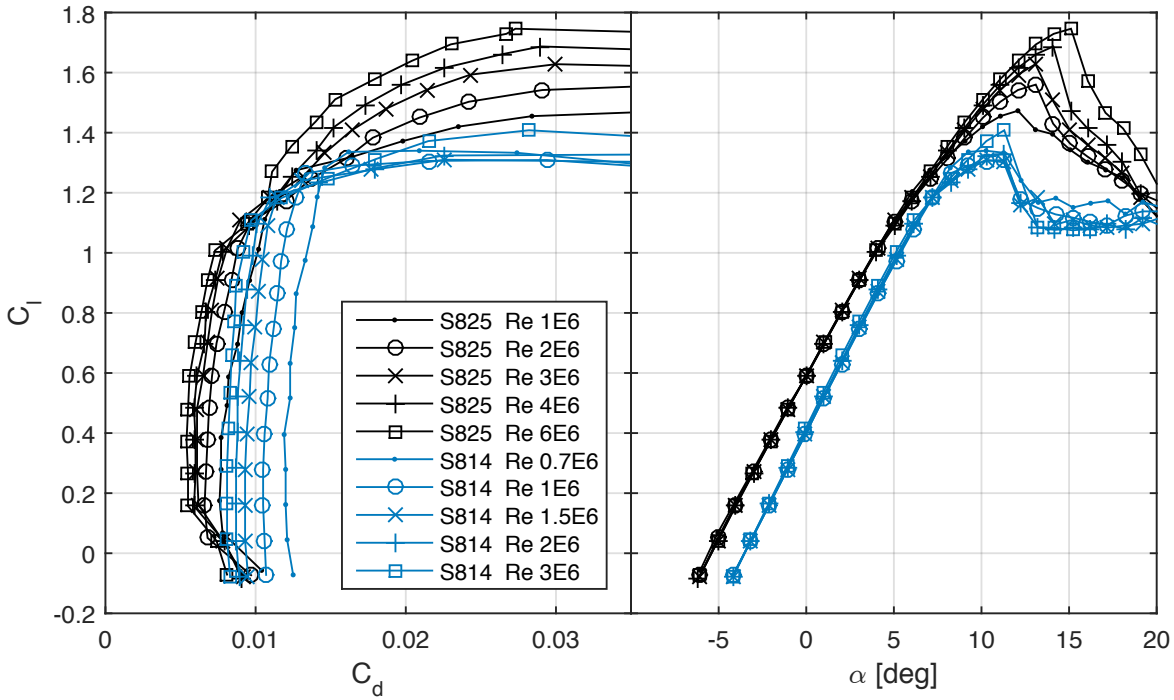
- $Re_c \approx$ 2,000,000
- high quality, public, and low turbulence wind tunnel data
- fixed transition, roughness, and unsteady data
- roughness insensitivity
- thickness requirements

Airfoil Selection

S814 ($\frac{t}{c} = 0.24$) and S825 ($\frac{t}{c} = 0.17$)

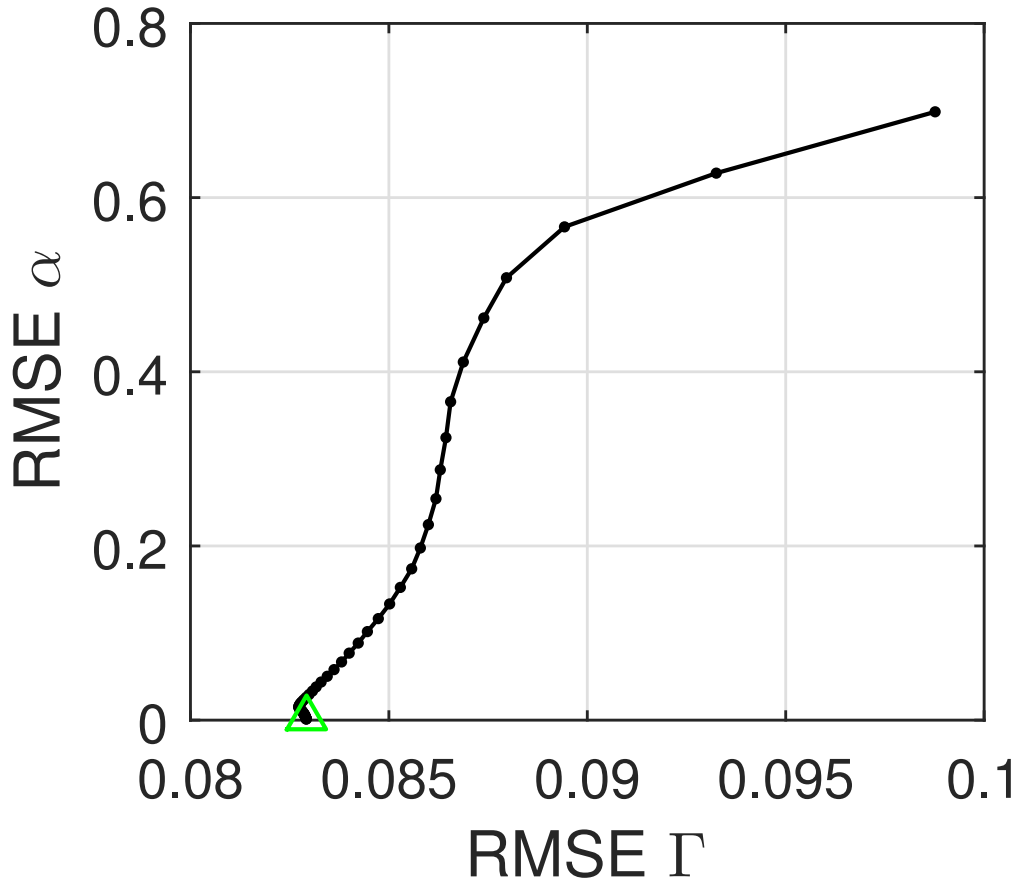




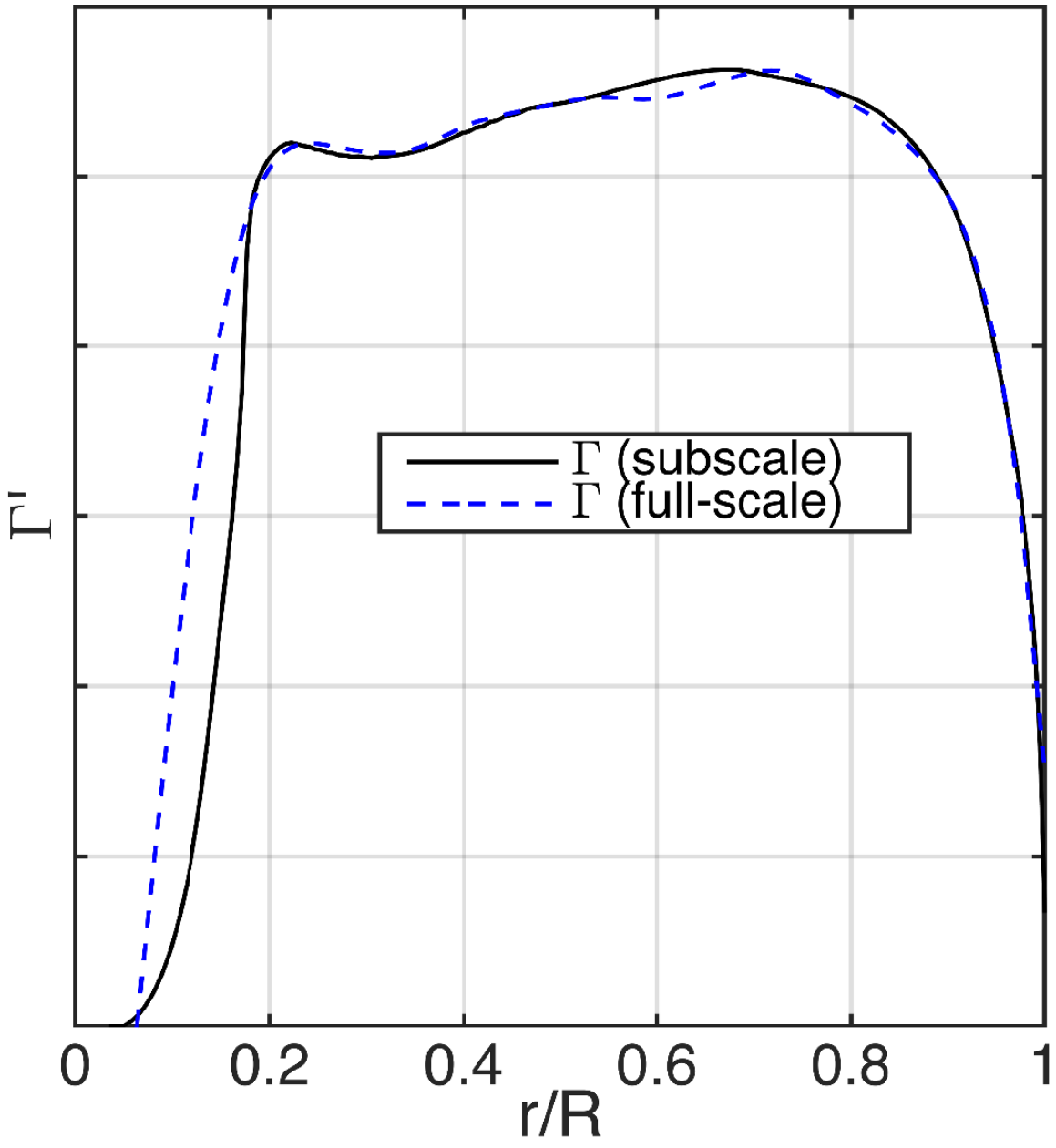


Inverse Design

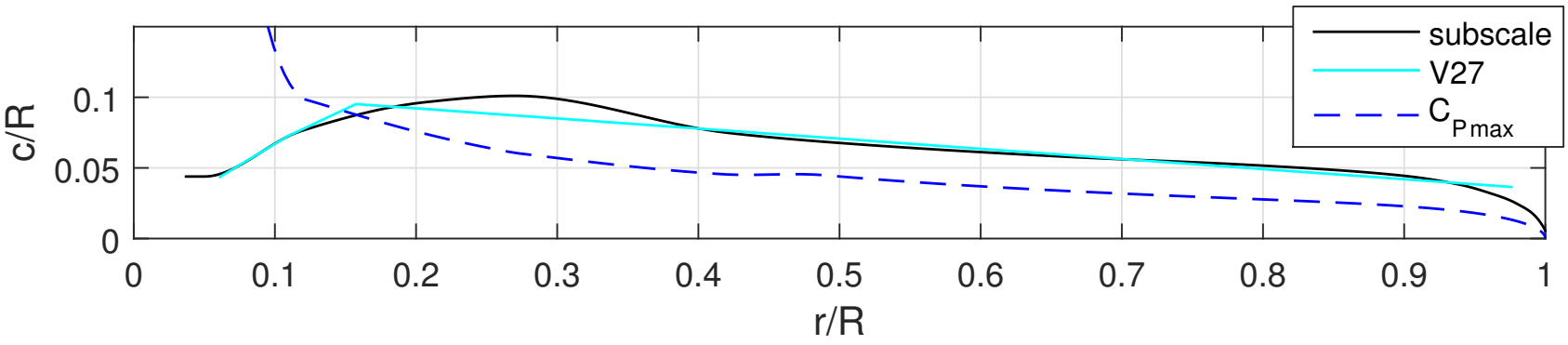
- created inverse design tool
- solved for chord and twist
- iterate with WT_Perf
- convergence of two objective functions

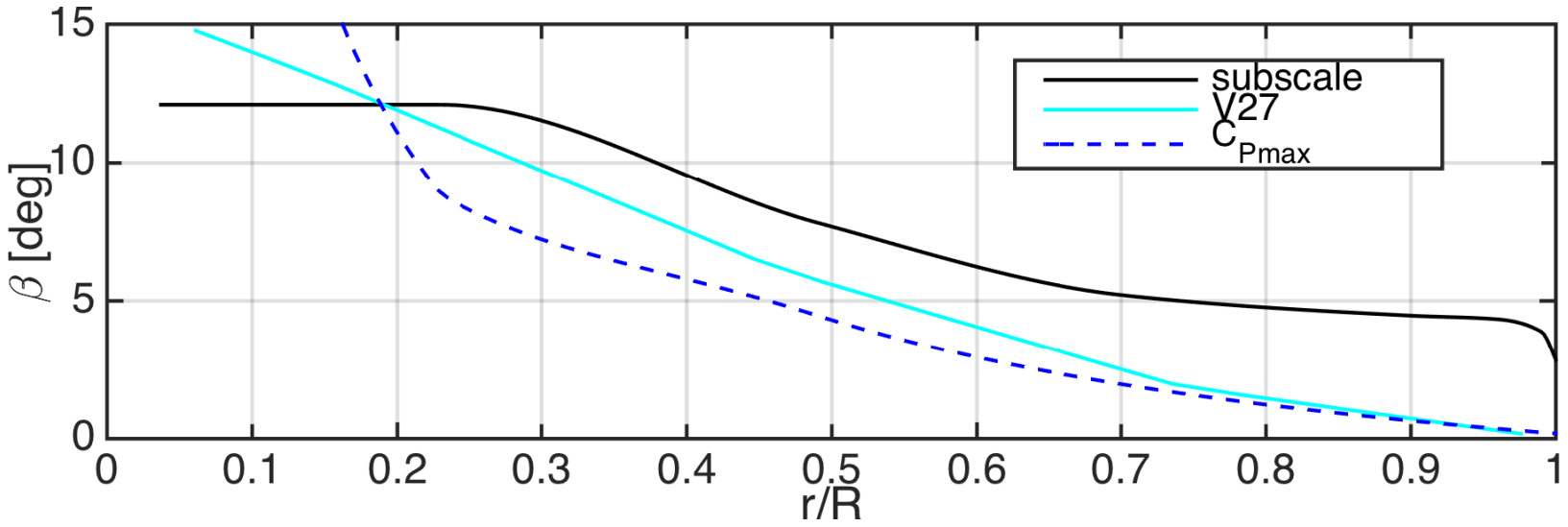


Circulation

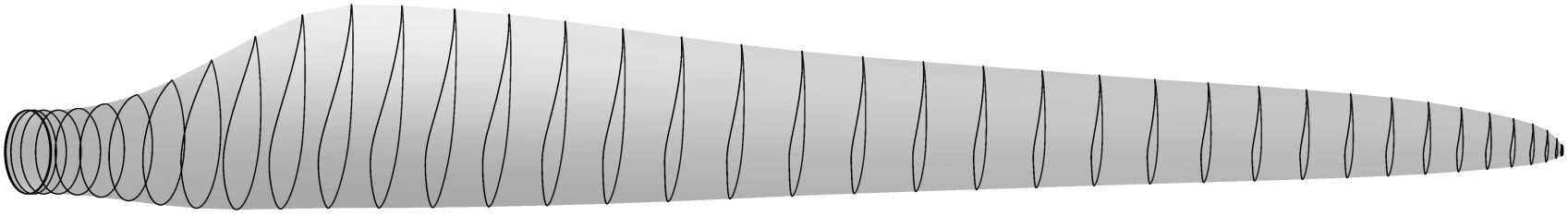


Geometry


c/R
0.1
0.05
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
r/R
subscale
V27
C Pmax


β [deg]
15
10
5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
r/R
subscale
V27
C Pmax

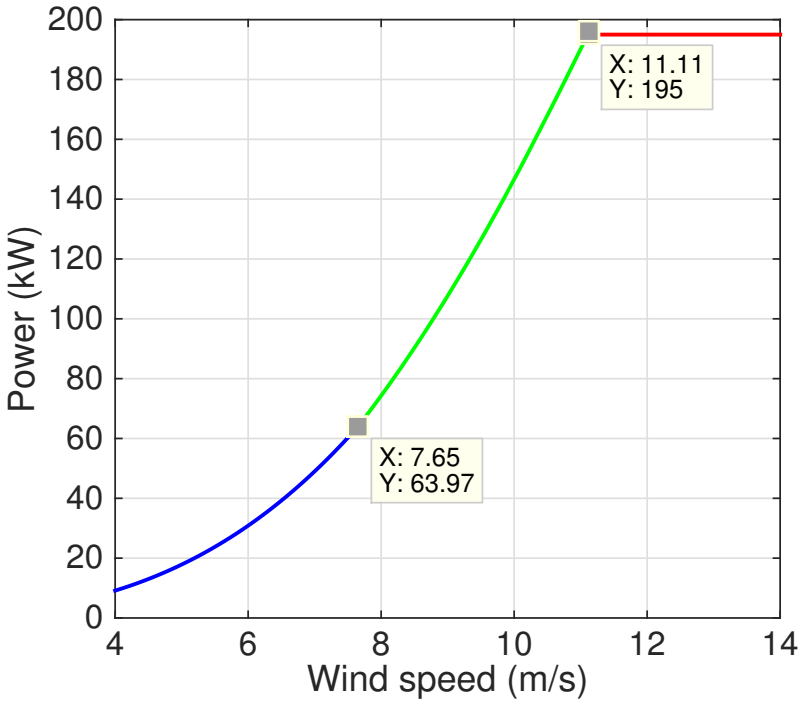
NRT Blade

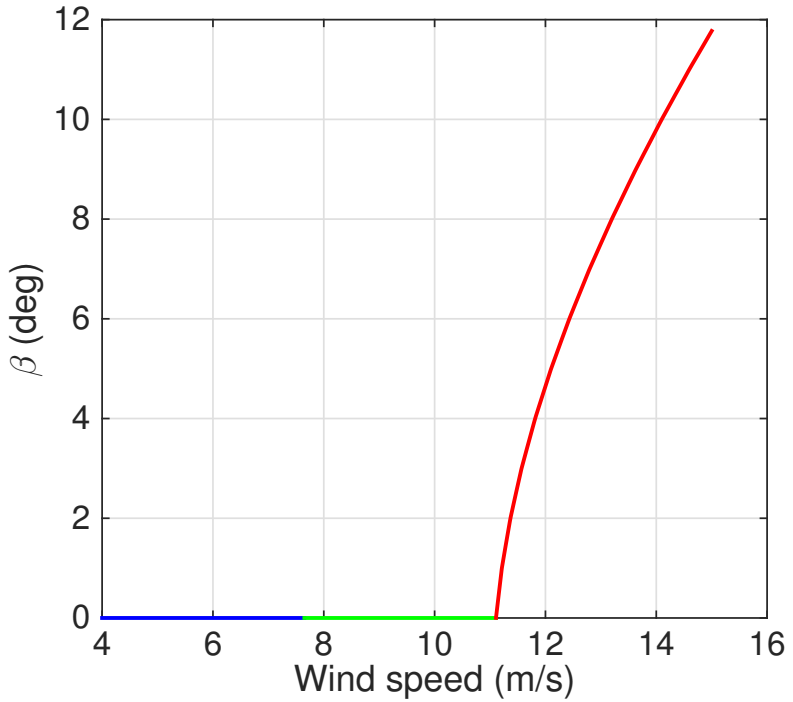


NRT Blade

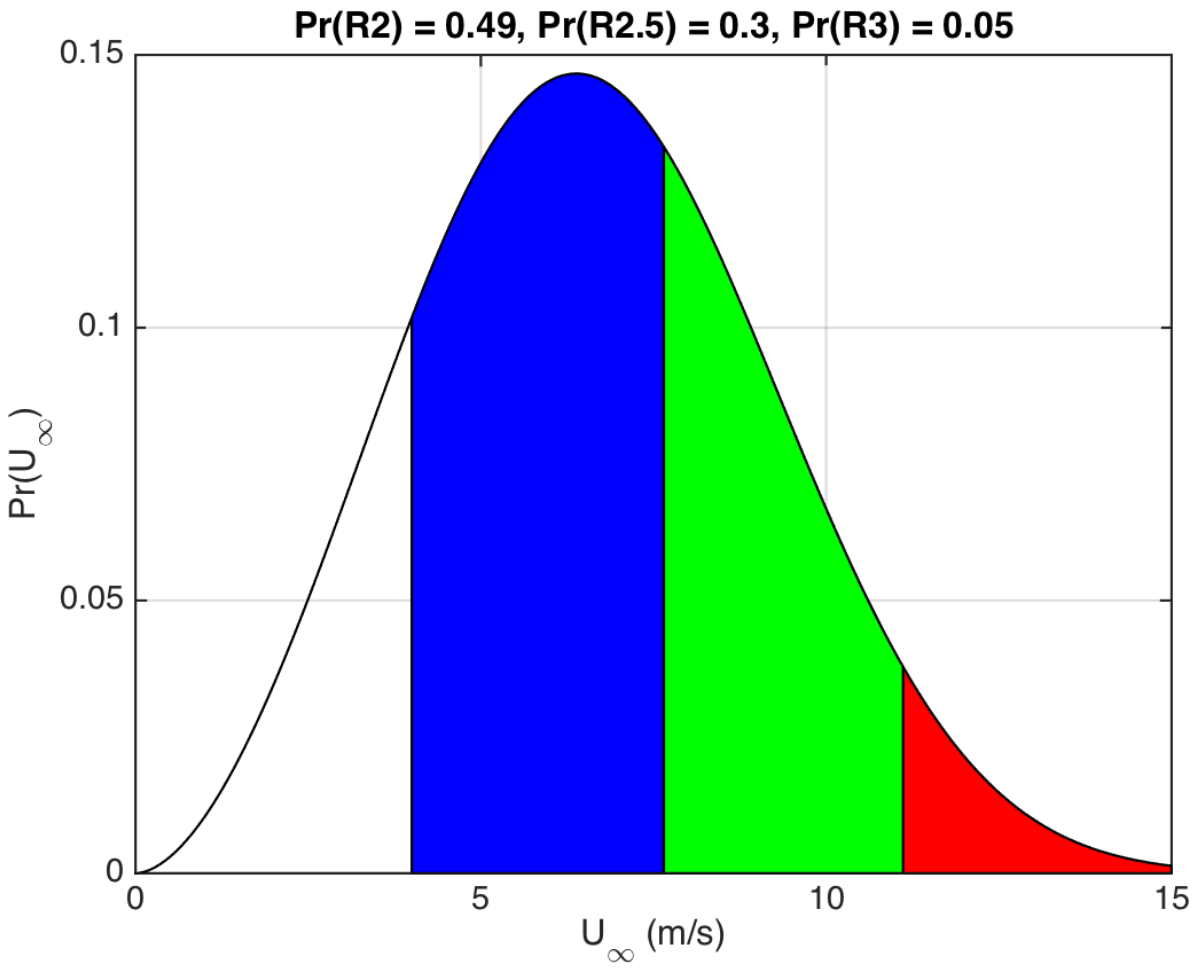
(nrtu3d.u3d)

Predicted Performance



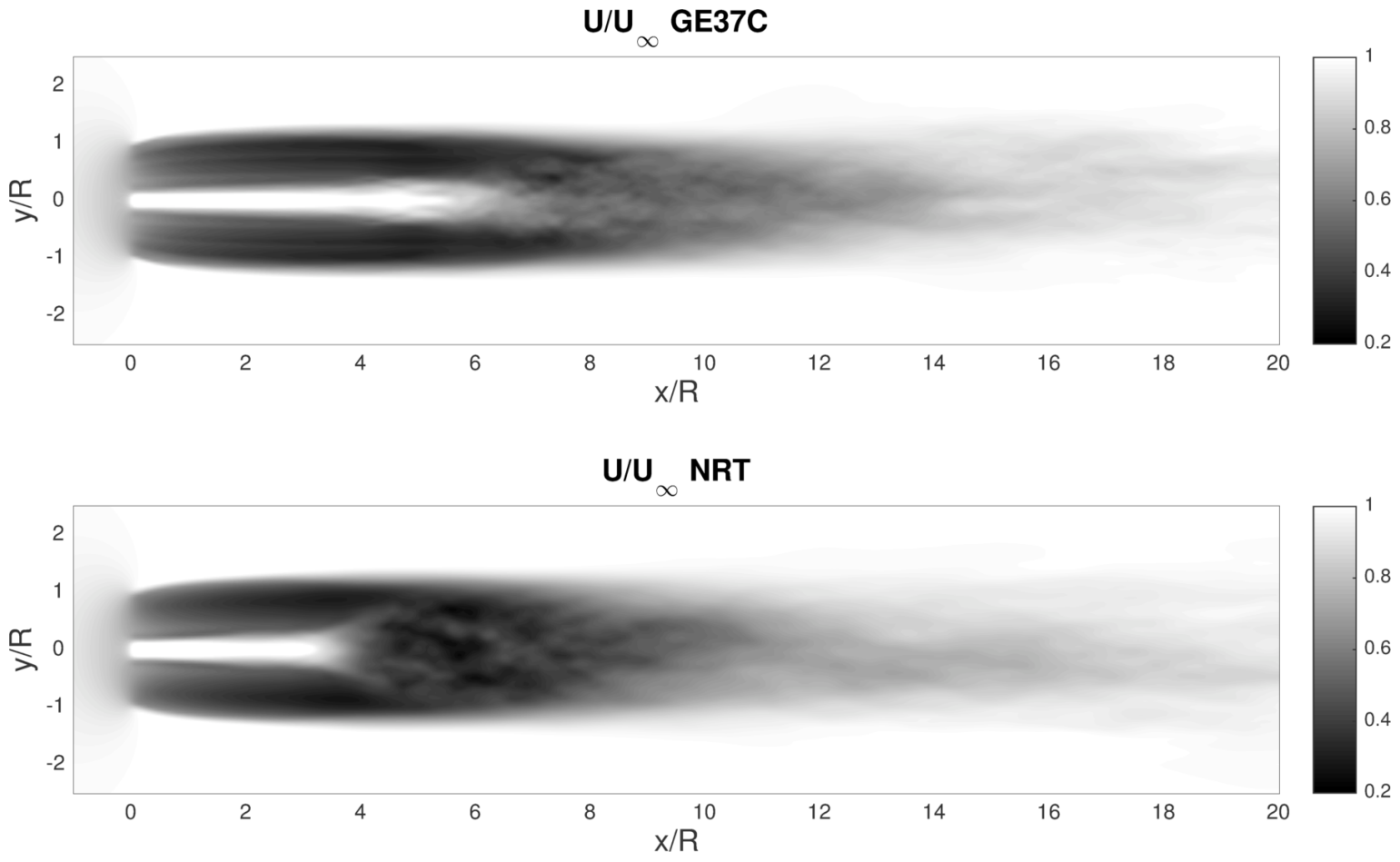


Predicted Performance

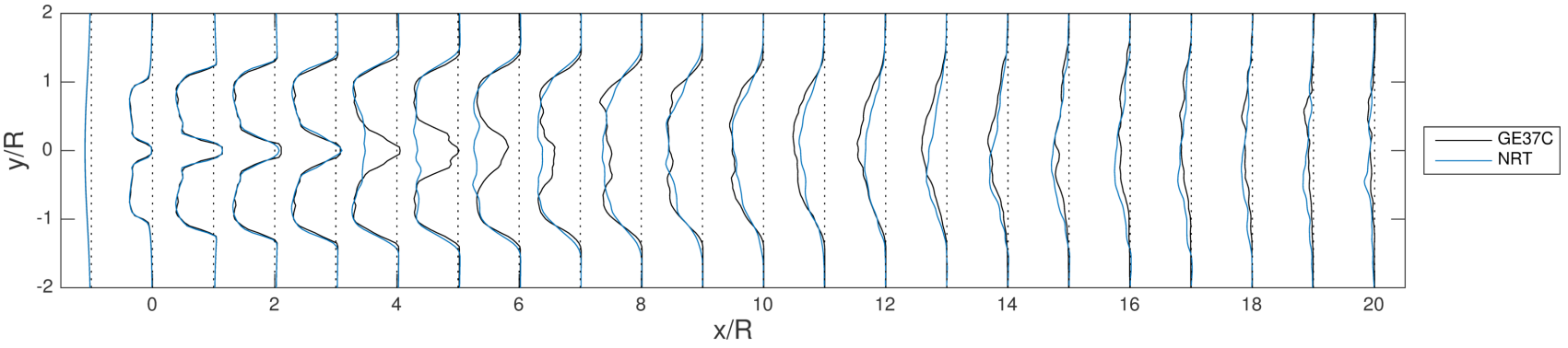


D [m]	λ_{R2}	σ [%]	P_{rated} [kW]	$C_{P_{R2}}$	$C_{T_{R2}}$	Pr(R2)	Pr(R2.5)	Pr(R3)	cf	AEP [GWh]
27	9	6.4	195	0.462	0.863	0.49	0.30	0.05	0.30	0.51

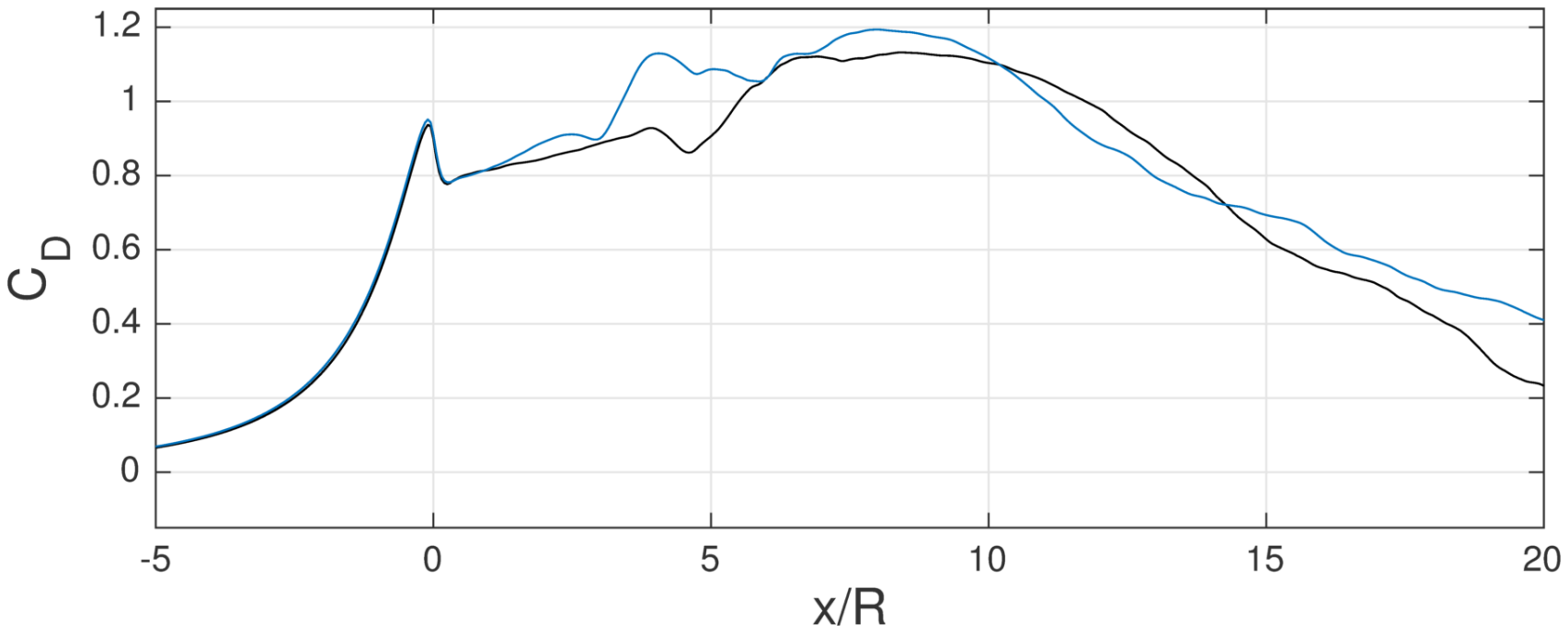
Free Wake Vortex Simulation - CACTUS



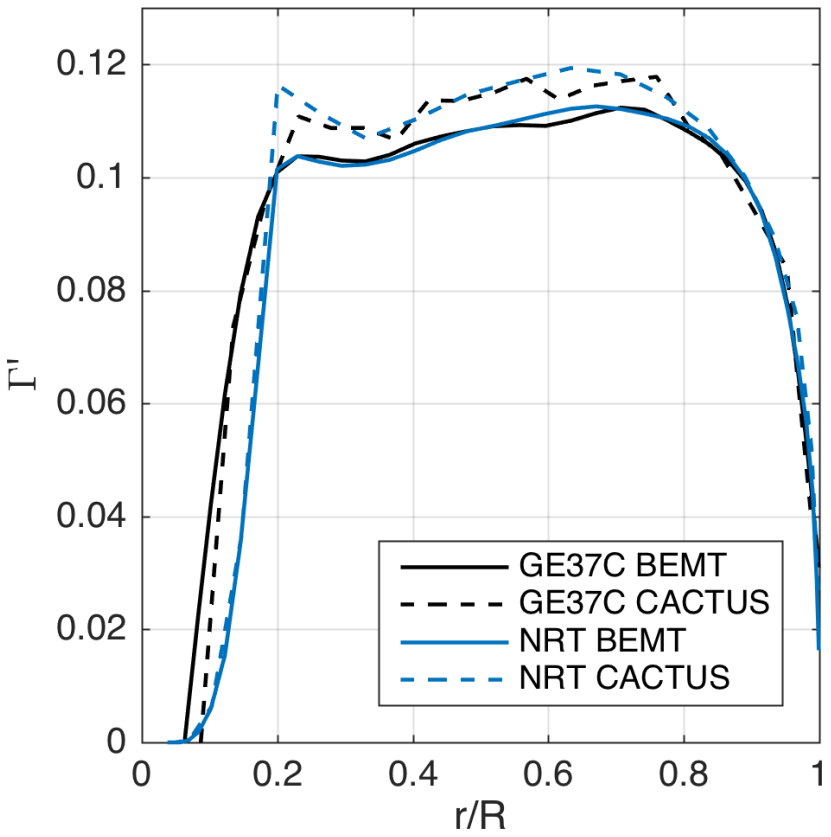
Average Axial Velocity



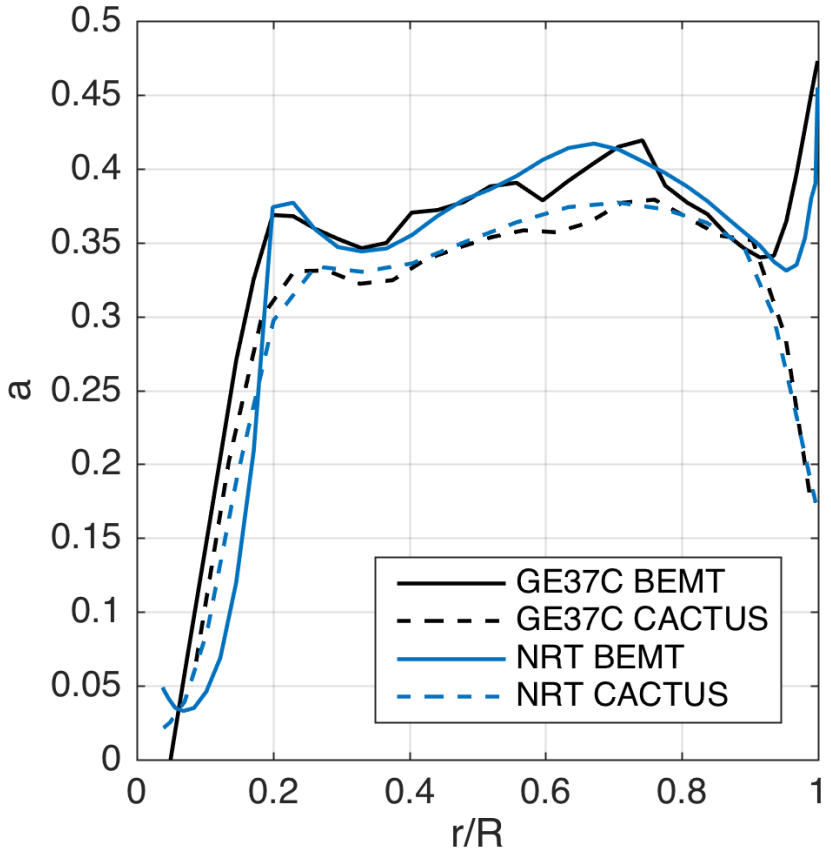
Momentum Recovery



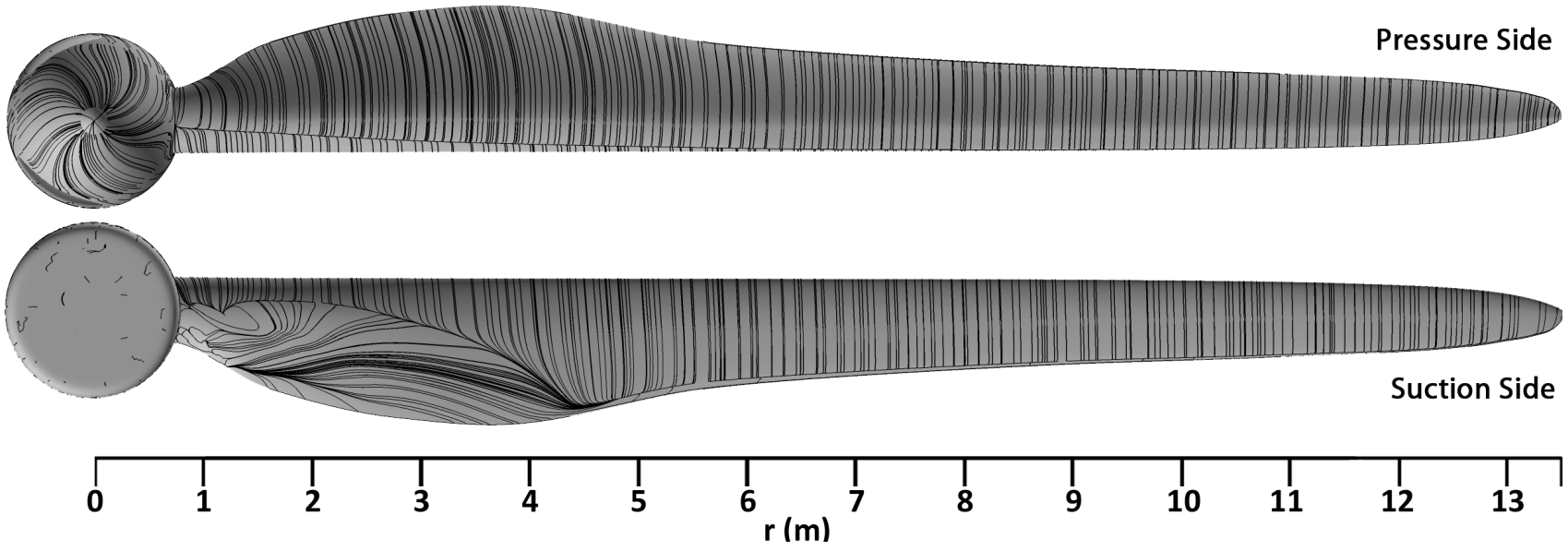
Dimensionless Circulation, Γ'



Axial Induction, a



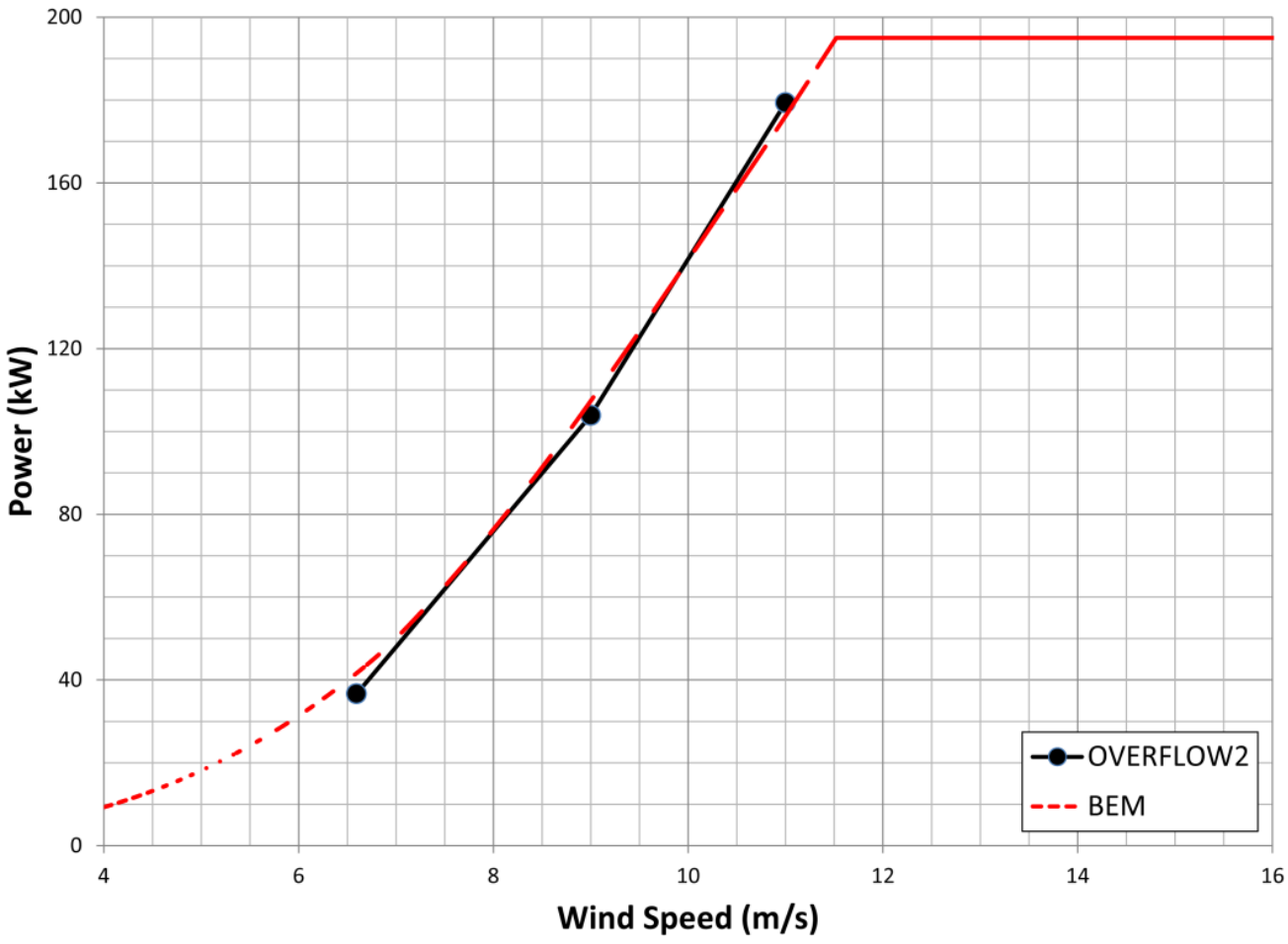
3D CFD, 11 m/s



2D BEMT agrees with 3D CFD separation location

3D CFD

3D flow effects and uncertainty of root section performance not an issue



Other Topics

- Re_c and Re_D
- Near wake is created by a distribution of forces, sufficient to create equal far wake mixing and recovery?
- Turbulence intensity created largest differences in wake recovery in LES

Table: Wake Reynolds Number, Re_D

scale	$Re_D \times 10^{-6}$	U_∞ (R2)	D (m)
subscale	7–12	4–8	27
full-scale	23–38	5–8	77

Aeroelasticity

- Lock Number: ratio of aerodynamic to inertial forces
- Similarly, time rate of change of circulation
- Would create equal gust response

$$C_{l_\alpha} \frac{c}{R} \frac{h_0}{R} \left(\frac{\omega_h}{\Omega} \right)^2 \lambda^2 = K \tag{1}$$

Aeroacoustics

- Tip and airfoil self-noise acoustic power: $SWL \propto (\Omega R)^5$
- NRT designed to have same max tip-speed as full-scale (≈ 74 m/s)