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Scaled Wake Research at Swift

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Outline

- Aerodynamic design of NRT blades to create a scaled wake
  Other scaling topics
- Characteristics of the wind for different size rotors
  Atmospheric conditions at Swift

Scaling Perspective

- Wind turbines will continue to become larger
- Wind turbine designs can be scaled, but not every dimensionless parameter can be kept constant
- Estimate which dimensionless parameters are most important for research goals
- Experiment at a scale that meets scientific and budgetary goals

Example

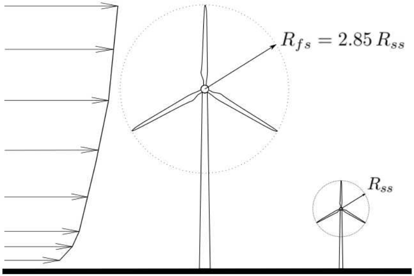
A wind turbine that is scaled down to wind tunnel size will have a lower C_P because L/D ratio is sensitive to Re_c

NRT Design Motivation

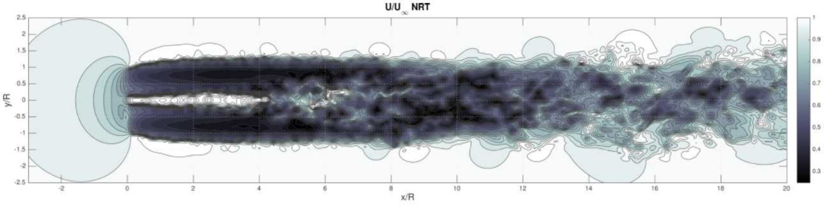
- To better understand wind turbine wakes
- Study effects of rotors on downwind turbines

Aerodynamic Objective

- Design wind turbine blades to be manufactured and flown for research on wakes in an array
- Create same initial conditions velocity/momentum deficit at rotor plane as fullscale machine
- What shape does the blade need to produce scaled wake?



A Scaled Wake

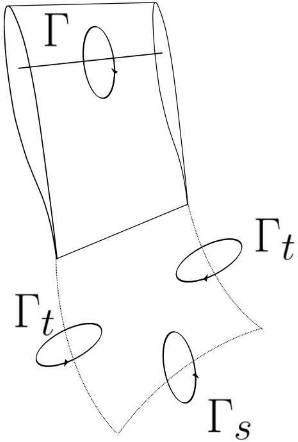


Create the same velocity field, $\frac{U}{U_\infty}$

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
- $C_l = 0.6$

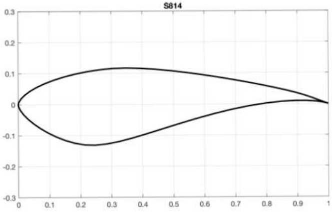
$$\Gamma'\left(\frac{r}{R}\right) = \frac{C_l}{2}\frac{W}{U_\infty}\frac{c}{R}$$

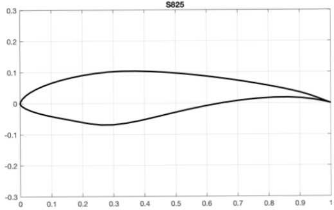
Airfoil Selection Criteria

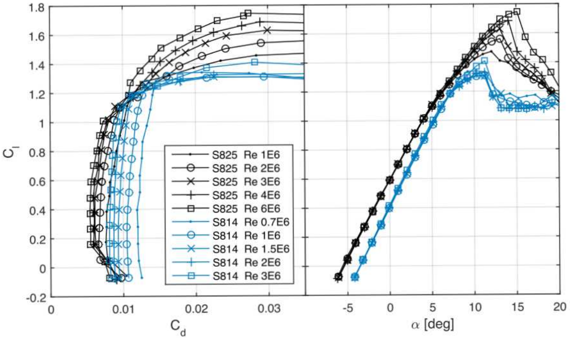
- $Re_c \approx 2{,}000{,}000$
- high quality, public, and low turbulence wind tunnel data
- fixed transition, roughness, and unsteady data
- roughness insensitivity
- thickness requirements

Airfoil Selection

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

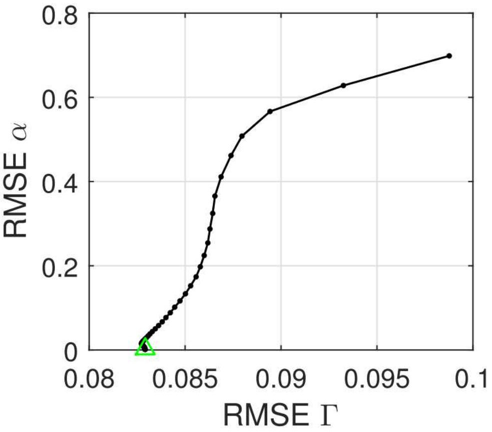




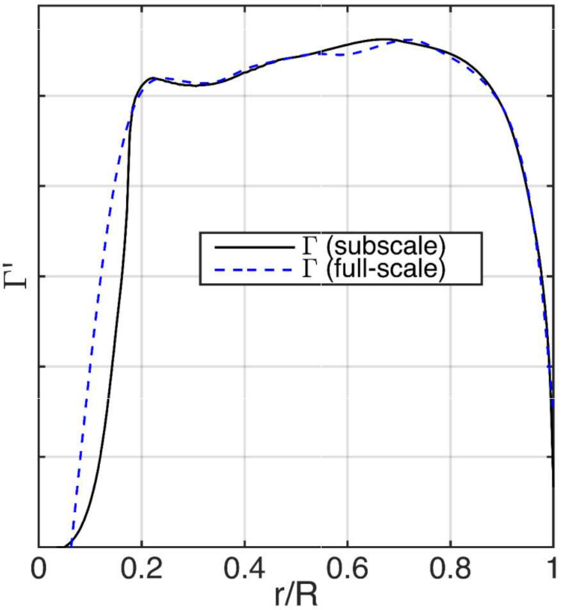


Inverse Design

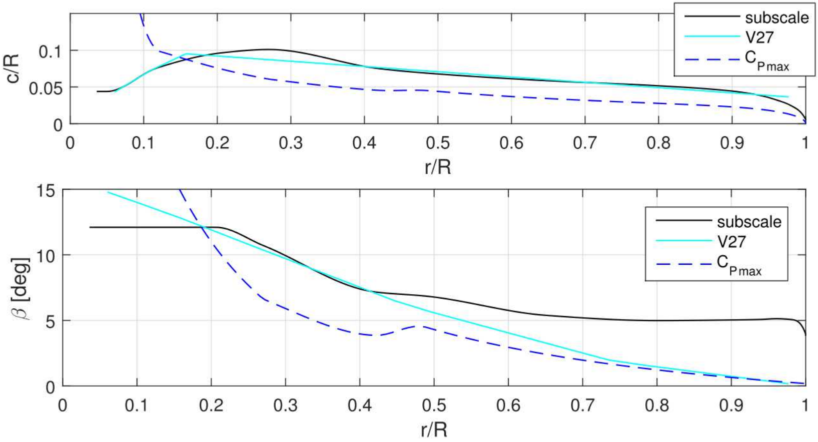
- created inverse design tool
- solved for chord and twist
- iterate with WT_Perf
- converge of two objective functions



Circulation

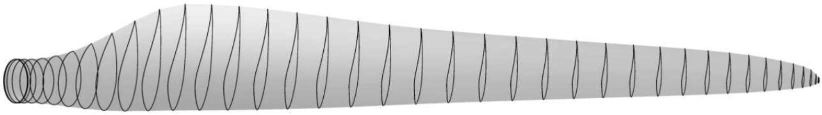


Geometry



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
$C_{P\,max}$
15
10
5
0
β [deg]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
r/R
subscale
V27
$C_{P\,max}$

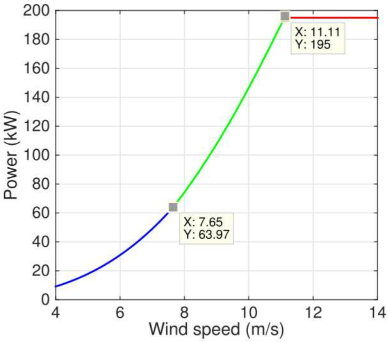
NRT Blade

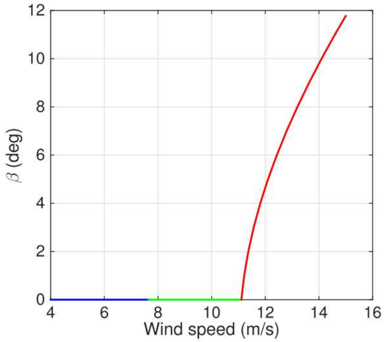


NRT Blade

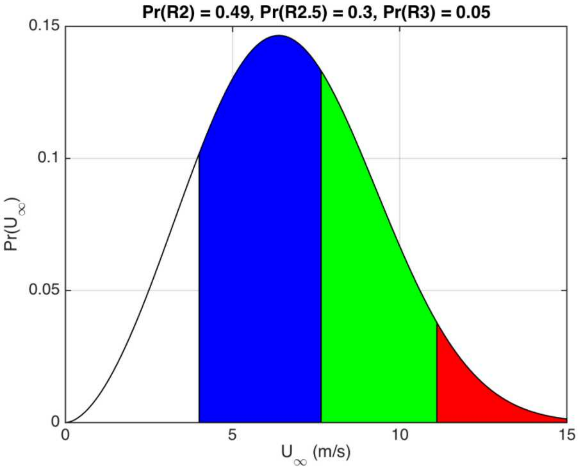
(nrtu3d.u3d)

Performance



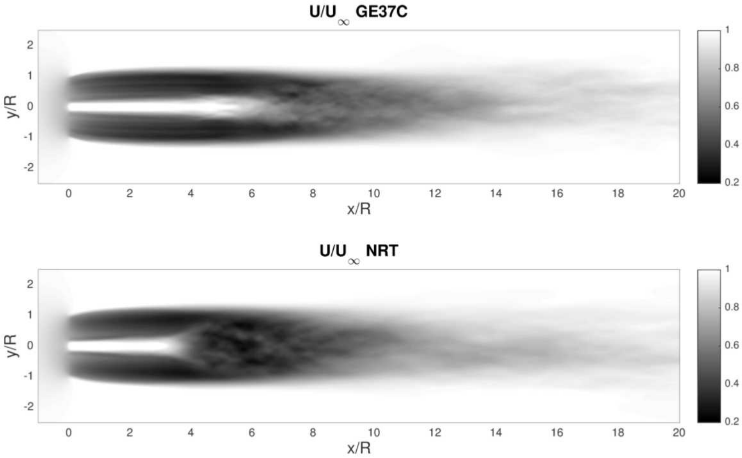


Performance

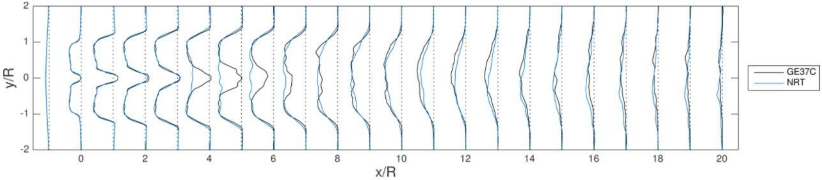


D [m]	λ_{R2}	σ [%]	P_{rated} [kW]	$C_{P_{R2}}$	$C_{T_{R2}}$	Pr(R2)	Pr(R2.5)	Pr(R3)	cf	AEP [GWh]
27	9	6.4	195	0.462	0.863	0.49	0.30	0.05	0.30	0.51

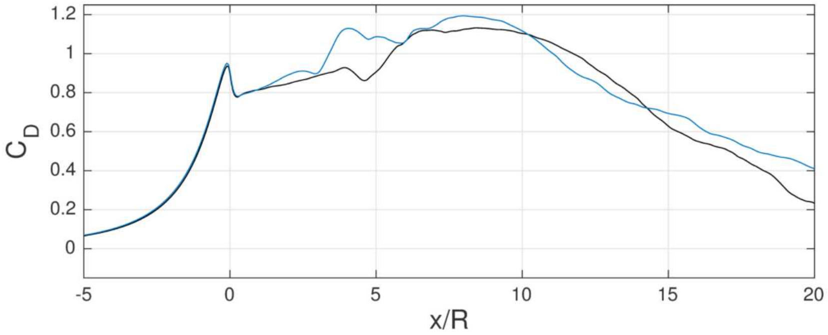
Free Wake Vortex Simulation - CACTUS



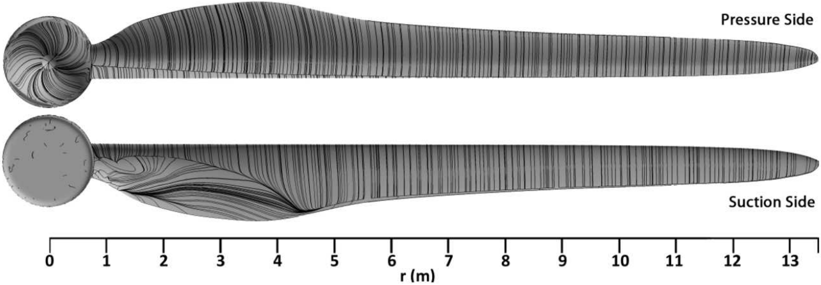
Average Axial Velocity



Momentum Recovery



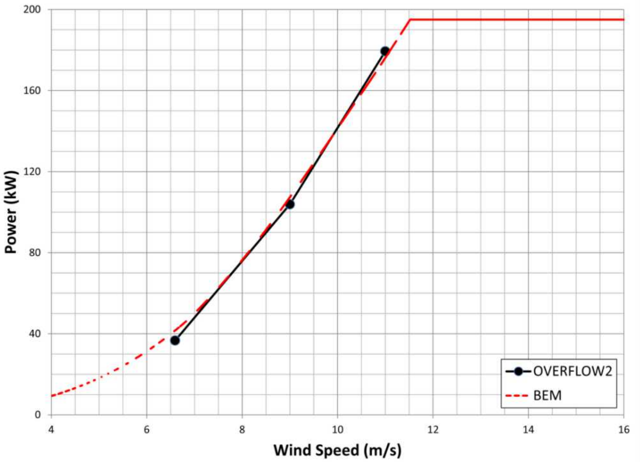
3D CFD, 11 m/s



2D BEMT agrees with 3d CFD separation location

3D CFD

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



3D Printed Blade Mold at Oakridge

Blade Design and Functional Scaling

✓ Designed to Scale

- $\Gamma'(\frac{r}{R})$ 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), and the axial velocity of the near wake
- Tip-speed-ratio, λ, for equal tip vortex spacing and parallel streamlines
- Equal initial conditions for velocity field in wake (U/U_∞)
- 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

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

- 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

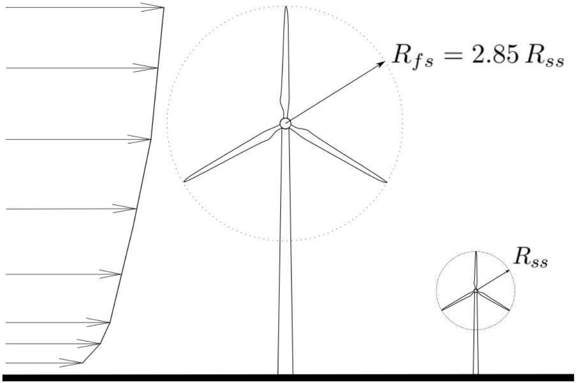
- Tip and airfoil self-noise acoustic power: $SWL \propto (\Omega R)^5$
- NRT designed to have same max tip-speed as full-scale (≈ 74 m/s)

NRT Conclusions

- Parameters were chosen to create scaled wake of GE 1.5 MW machine
- NRT scaled wake experiments will confirm Γ', λ, a, C_T, are important to wake structure

Comparing Inflow Conditions

- Data from TTU 200 m meteorological tower
- Compare probability of subscale and full-scale inflow conditions



Scaled Inflow - Dimensionless Quantities

shear

$$\tau^* = \frac{U_t - U_b}{U_h} \tag{2}$$

turbulence intensity

$$TI = \frac{\sigma(U_h)}{\overline{U}_h} \tag{3}$$

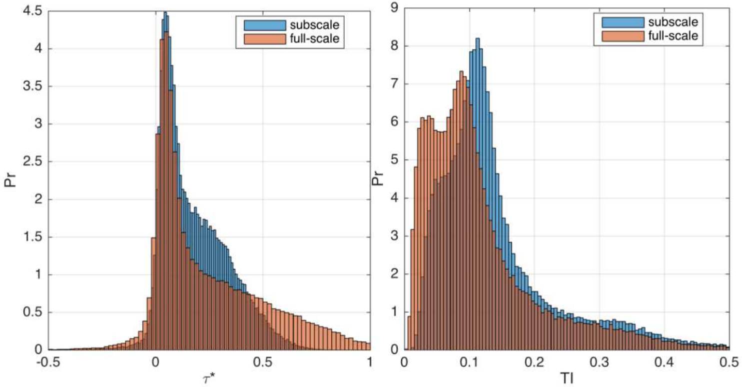
veer

$$V = \theta_t - \theta_b \tag{4}$$

lateral turbulence intensity

$$LTI = \frac{\sigma(\theta_h)}{\overline{\theta}_h} \tag{5}$$

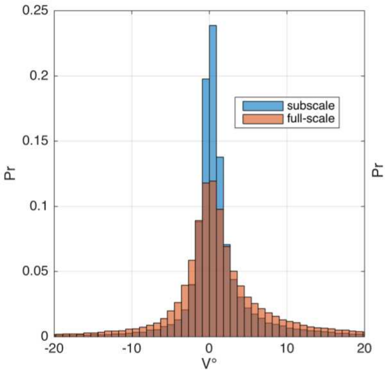
SWiFT Wind Resource

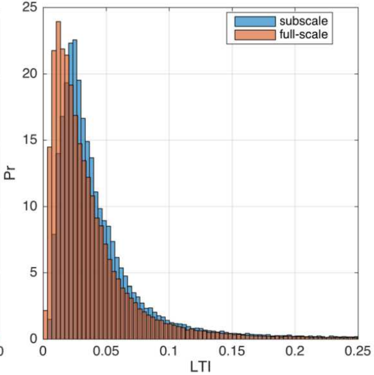


shear has equal modes

turbulence has equal ranges

SWiFT Wind Resource

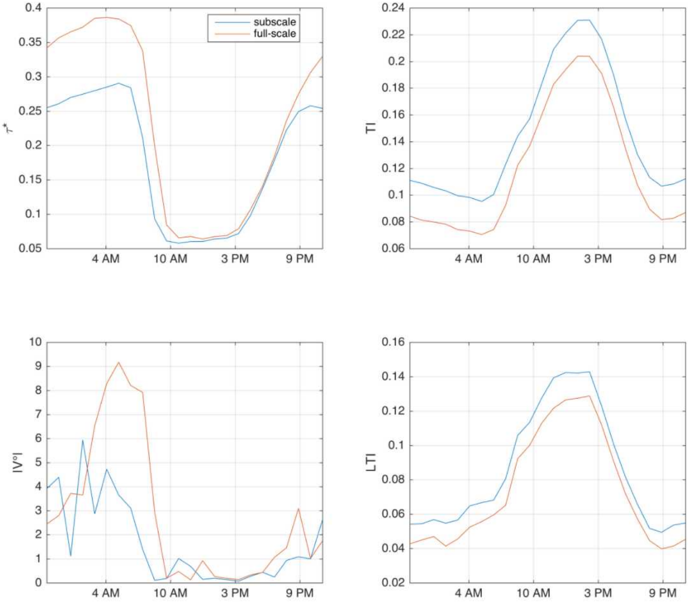




0 V_{ss} more common

higher TI_{ss} causes more $\sigma(\theta_{ss})$

SWiFT Average Day



Inflow Conclusions

- Inflow conditions may not be equal at same instant of time
- May need to wait longer for rarer event at subscale
- Range of TI, V, and LTI equivalent
- Late morning and afternoon average shear and veer are equal between scales
- Full-scale turbines occasionally see higher shear above 75% (Pr = 5%)

Conclusions

- NRT designed to create scaled wake
- One design cannot do it all
- Scaling is always important as blades continue to become larger
- Range of inflow conditions well represented at SWiFT