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Aerodynamic Design Drivers of NRT Blade

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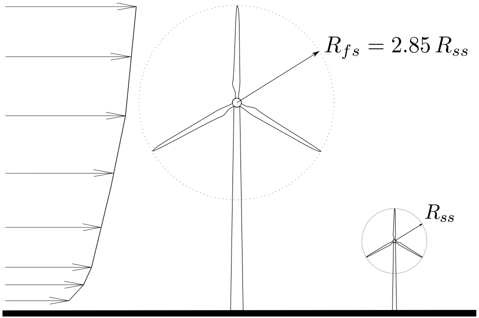
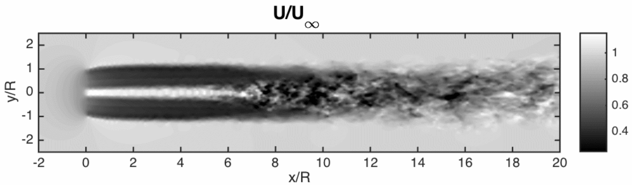
Aerodynamic Objective

Create a scaled wake of a GE37c wind turbine with new blades installed at SWiFT
What shape does the blade need to produce scaled wake?



A Typical Wake



What Is a Scaled Wake?

- A scaled wake should have equal instantaneous velocity vectors, u_i/U_∞, at the same spatial positions, x/R, y/R, z/R at any time, $t\,U_\infty/R$.

- If the scaled velocities are equal in time and space, wake characteristics also are equal. Tip vortex pairing and entrainment of momentum occur at same scaled positions downstream x/R. Meandering of wakes occur at same Strouhal number. And dissipation of large coherent structures to turbulence happen at the same rate.

Generating a Scaled Wake with Similarity?

- Kinematic, dynamic, and geometric similarity ensure experiment on sub-scale model is identical to testing full-scale wind turbine.

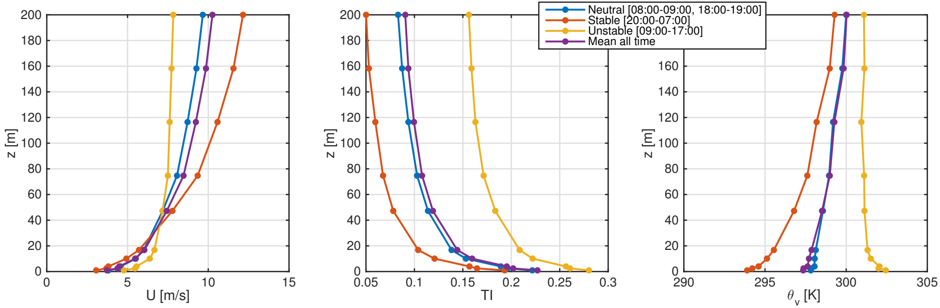
Kinematic Similarity

- Scaled wake should have kinematic similarity so that wake helix angles are identical and a blade station at a normalized radius fraction r/R sees the same relative inflow velocity, W/U_∞. So $\lambda_{fs} = \lambda_{ss} \therefore \Omega_{ss} = 2.3\Omega_{fs}$.
- The time averaged shear and turbulence intensity across the swept rotor area should be equal

Requirement 1

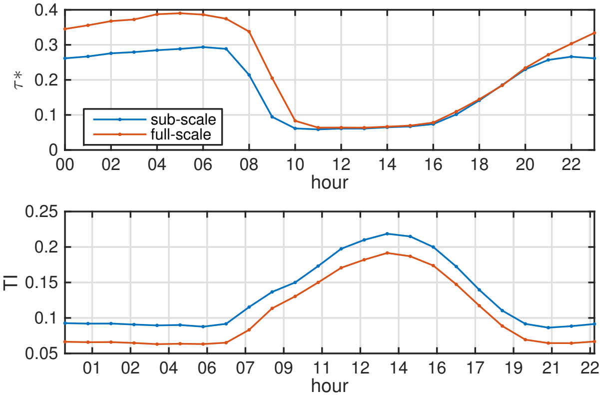
$\lambda_{ss} = \lambda_{fs} = 9$ in Region II

Mean Atmospheric Boundary Layer at SWiFT



D [m]	P [MW]	z_{hub} [m]	$U_{\infty hub}$ [m/s]	τ^*	TI
27	0.250	32.1	6.81	0.185	0.130
77	1.5	80	8.59	0.233	0.105

Average Day at SWiFT



Shear matches 11:00–20:00 local time

TI 2.5% consistenly high all day

Requirement 7 Effect of Scale on BL

Dynamic Similarity

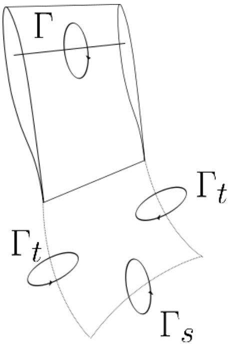
- Ratio of forces equal, e.g. $\frac{L_{ss}}{L_{fs}} = \frac{D_{ss}}{D_{fs}}$
- Viscous and inertial forces cause energy cascade and dissipation at equal rates
- Dynamic similarity is not possible:

$$\left(\frac{U_\infty \frac{r}{R} \lambda c}{\nu}\right)_{fs} \stackrel{?}{=} \left(\frac{U_\infty \frac{r}{R} \lambda c}{\nu}\right)_{ss} \quad \therefore 3.6 \neq 1. \tag{1}$$

$$(L/D)_{ss} \neq (L/D)_{fs} \tag{2}$$

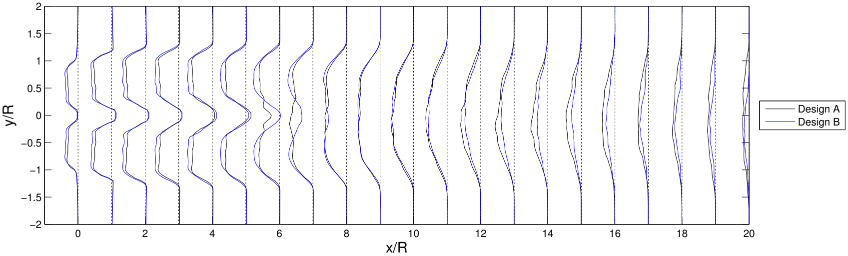
How is Wake Created?

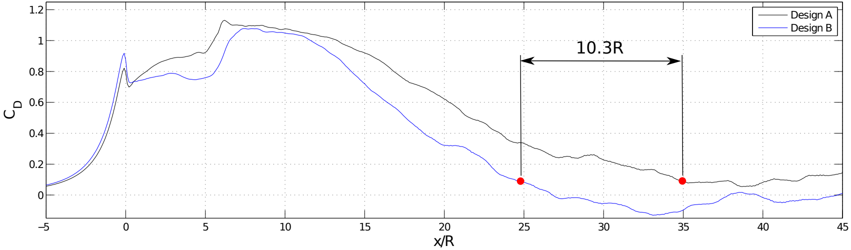
From lifting line theory and Kelvin's circulation theorem.



Shed circulation is determined by local spatial and temporal derivatives of bound circulation.

How Circulation Affects Wake





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Partial Dynamic Similarity

Therefore give up geometric similarity, but loosely keep dynamic similarity to ensure wake is generated by identical circulation

$$\Gamma'\left(\frac{r}{R}\right) = \frac{\Gamma(\frac{r}{R})}{RU_\infty} = \frac{C_l}{2}\frac{W}{U_\infty}\frac{c}{R} \tag{3}$$

Requirement 2

$\Gamma'_{ss} = \Gamma'_{fs}$ in Region 2

Unsteady Dynamic Similarity

Blade elasticity, turbulent inflow, shear, and yaw creating time-varying changes in circulation

$$\frac{d\Gamma'_{ss}}{dt^*} = \frac{d\Gamma'_{fs}}{dt^*} \quad (4)$$

Requirement 4

$$C_{l_\alpha} \frac{c}{R} \frac{W}{U_\infty} \frac{d\alpha}{dt^*} + C_l \frac{c}{R} \frac{d(\frac{W}{U_\infty})}{dt^*} = K \quad (5)$$

in Region 2

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Unsteady Dynamic Similarity

Example: only blade elasticity $h = h_0 \, e^{-i\omega_h t}$
for small angles of attack $\alpha = \frac{\dot{h}}{\lambda r/R}$

Requirement 4

$$C_{l_\alpha} \frac{c}{R} \frac{h_0}{R} \left(\frac{\omega_h}{\Omega}\right)^2 \lambda^2 = K. \tag{6}$$

Aerodynamic Scaling Strategy

- Relax geometric and Re scaling constraints
- Match circulation to create the same wake
- No Similarity - Re, $\frac{c}{R}$, β, C_l, airfoil shape, $\frac{d\Gamma'}{dt^*}$
- Kinematic similarity - λ in Region 2, Shear conditions match from 11:00–20:00
- Dynamic Similarity - Γ'
- TI 2.5% consistently high all day
- Need inverse design tool to find sub-scale geometry
- Choose appropriate airfoils at lower Re