Comparison of Mean and Dynamic Wake Characteristics between Research-Scale and Full-Scale Wind Turbines

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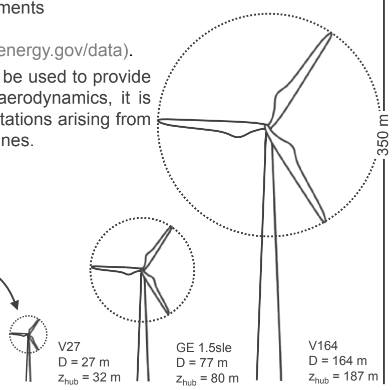
Abstract Comprehensive, utility-scale wake measurements from commercial wind plants are difficult to obtain. As a result, research in wind farm aerodynamics is often based on smaller-scale measurements and numerical experiments. It is therefore crucial for the scientific community to understand how results compare across scales. In this work, three actuator-line large-eddy simulations are performed to investigate the sensitivity of mean and dynamic wake characteristics to changes in hub height (for the same turbine model) and in rotor size and properties (for a research-scale and land-based-scale rotor at the same hub height). Results reveal that ground proximity has a large effect on wake expansion via turbulent transport of axial momentum and on the magnitude of lateral and vertical meandering. The different-rotor experiment suggests that wakes from different-scale turbines expand similarly when not limited by the ground, but that the meandering magnitude is not easily translatable across scales. Finally, the short-rotor wake recovers faster than the tall-rotor wake, but the far wakes of the different-sized rotors at the same absolute height are scalable.

Motivation

- It is difficult to obtain comprehensive data from commercial, full-scale wind plants.
- The Sandia National Laboratories' Scaled Wind Farm Technology (SWiFT) facility was designed for research and technology testing in wind energy and provides:
  - Flexibility to accommodate experiments
  - Extensive instrumentation
  - Freely available data (https://a2e.energy.gov/data).
- Although SWiFT measurements can be used to provide knowledge of full-scale wind plant aerodynamics, it is important to investigate potential limitations arising from the research-scale nature of the turbines.

Fig.1: The SWiFT facility [Source: GLEAMM]



Data

- Three large-eddy simulations of isolated rotor wakes (rotating actuator lines) using the National Renewable Energy Laboratory's SOWFA code
- Mesh of 5 km x 5 km x 2 km; grid spacing down to dx = dy = dz = 0.6 m in the wake
- Data analysis considers 20 minutes of simulation time at 1-Hz frequency
- Unstable conditions (low shear/veer); 7 m/s hub-height, planar-averaged wind speed.

Simulation	ABL Shear α_{ABL} [-]	Hub Height z_{hub} [m]	Wind Dir. $wdir_{hub}$ [deg]	Wind Spd. U_{hub} [m/s]	Turb. Intens. TI_{hub} [-]	Rotor Shear ΔU [m/s]	Rotor Veer Δwdir [deg]	C_T [-]
V27.32m	0.21	32.0	268	6.7	0.16	1.2	-0.1	0.71
V27.80m	0.18	80.0	272	6.8	0.13	0.4	0.0	0.72
GE.80m	0.18	80.0	272	6.8	0.13	1.0	0.0	0.83

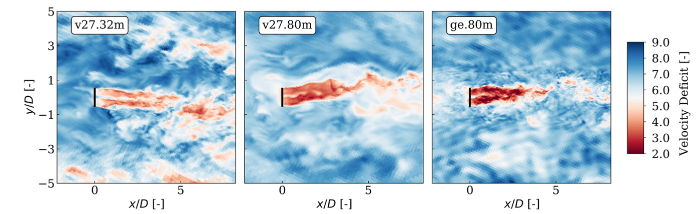


Fig.2: Horizontal snapshot of velocity deficit for simulations V27.32m, V27.80m, and GE.80m at hub height.

Hub-Height Experiment

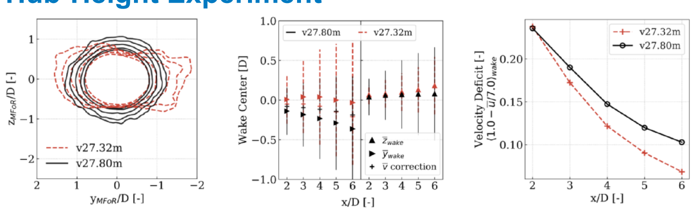


Fig.3: Wakes of V27.32m; V27.80m. Mean wake outline (x = 2-6 D) in a meandering frame of reference (MFoR) (left); wake center mean (i.e., deflection) and std. dev. (i.e., meandering) (center); and wake-averaged velocity deficit (c).

- The V27.32m wake senses the ground (which constrains vertical but not horizontal atmospheric motions) whereas the V27.80m wake expands symmetrically.
- The V27.32m wake deflects more in the lateral direction. This is a consequence of differences in the lateral inflow velocities (v) between the two simulations (see table in "Data" section). Applying a correction that accounts for these differences leads to comparable lateral deflection magnitudes.
- The V27.32m wake meanders more laterally and less vertically.
- Velocity deficit magnitudes are similar between the two simulations in the near wake, due to similar axial inflow at their respective hub heights.
- The V27.32m wake recovers faster.

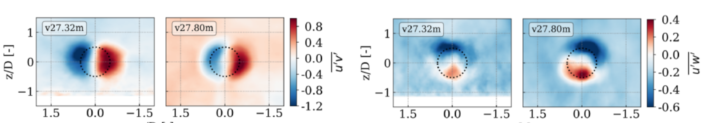


Fig.4: Shear stress $\overline{u'v'}$ (left) and $\overline{u'w'}$(b) at x = 2 D for V27.32m and V27.80m.

- In addition to advection and pressure-gradient and buoyancy forces, the momentum budget is also dictated by turbulent transport.
  - Higher values of $\overline{u'v'}$ for V27.32m are consistent with enhanced lateral expansion.
  - Lower values of $\overline{u'w'}$ for V27.32m are consistent with reduced vertical expansion.

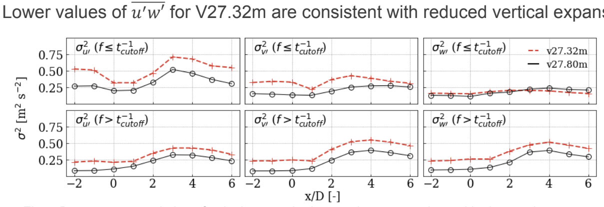


Fig.5: Downstream evolution of velocity perturbations variance as estimated by integrating power spectra for two frequency bands: below (top) and above (bottom) t_{cutoff} = 20 s.

- Higher values of low-frequency v' variance (w' variance, beyond 3 D) for the V27.32m (V27.80m) rotor can explain its larger lateral (vertical) meandering.

Different-Rotor Experiment

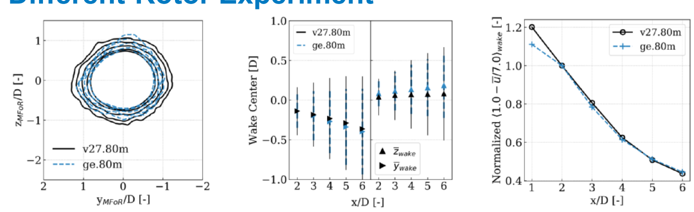


Fig.6: Wakes of V27.80m; GE.80m. Mean wake outline (x = 2-6 D) in a meandering frame of reference (MFoR) (left); wake center mean (i.e., deflection) and std. dev. (i.e., meandering) (center); and wake-averaged velocity deficit (c).

- The expansion pattern for both wakes is azimuthally symmetric, with the smaller rotor expanding more rapidly.
- Under identical inflow, the small rotor is expected to meander substantially more than the large rotor. Here the smaller rotor meanders more, but the differences are small.
- Both wakes recover at a similar rate beyond x = 2 D.

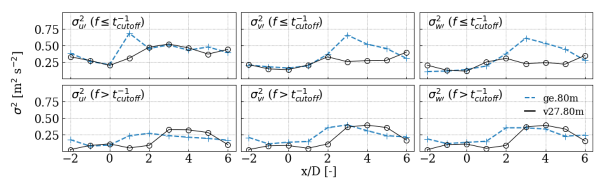


Fig.7: Downstream evolution of velocity perturbations variance as estimated by integrating power spectra for two frequency bands: below (top) and above (bottom) t_{cutoff} = 2 D / 7 m/s ~ 22 s (GE.80m) and ~ 8 s (V27.80m).

- Low-frequency v' and w' variances are higher for the large-rotor wake.
- High-frequency variances track together for both wakes, with a delay for large rotor.

Conclusions

- Ground proximity:
  - Has a large effect on wake expansion via turbulent transport of axial momentum, which is limited in the vertical direction and enhanced in the lateral direction.
  - Accelerates wake recovery, since the rotor operates in a more turbulent environment.
- Rotor size:
  - Can affect the wake expansion rate, but does not seem to affect the velocity deficit recovery rate beyond the near wake.
  - Affects wake meandering, which cannot be quantified by considering atmospheric inflow alone (inflow is described in the table in "Data" section).
- Ongoing work considers: longer simulation time; other atmospheric conditions; 3 distinct rotors in the same inflow (including a larger, offshore-scale rotor); more in-depth turbulence analyses conducted in a meandering frame of reference.

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