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Comparison of upwind and downwind operation of the NREL Phase VI Experiment

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Abstract. Wind tunnel data are presented comparing upwind versus downwind operation of the National Renewable Energy Laboratory's Phase VI wind turbine. Power was not reduced as expected with downwind operation, which may be attributed to inboard three-dimensional effects. Average flap bending loads were reduced with downwind coning and compared well with prediction. Blade fatigue loads were increased with downwind operation; however, fatigue was mitigated with an aerodynamic tower shroud (fairing). The shroud needs to remain aligned with the freestream, demonstrated by an increase in fatigue loads from a 10° error in shroud alignment. Pressure data were acquired of the tower wake at the rotor location with and without the shroud installed. The bare-tower wake data compared well with previously published work. The shroud wake data at 10° error in alignment showed velocity reduction and turbulence approaching the bare tower values. Downwind operation, with an aligning tower shroud, should be considered for future designs given the load benefits of downwind coning.

1. Introduction

The predominant wind turbine configuration currently is horizontal-axis, three-bladed, upwind rotors (rotor upwind of tower). Several large downwind research turbines were constructed in the past; examples of these in the United States were the 100 kW MOD-0 [1] and the Hamilton Standard 4 MW WTS-4 [2], which were government-sponsored research projects in response to the energy crises of the 1970's. Smaller downwind turbines available commercially in the 1980's were the 80 kW ESI-80 and the 25 kW Carter [3]. Downwind turbines have the potential for lower average blade and yawing loads and thus lower mass/cost; however, problems such as fatigue and noise arise from the rotor interacting with the tower wake. Recent advances in offshore wind energy, including turbines on floating platforms, has renewed interest in large downwind designs that can be placed far from shore. Ichter, Steele, Loth, Moriarty, and Selig [4] present a large downwind concept, which was the inspiration for this writing.

This paper reports on unpublished data from the National Renewable Energy Laboratory's (NREL) Unsteady Aerodynamics Experiment (UAE) Phase VI [5] which was obtained at the National Full-Scale Aerodynamics Complex 80- by 120-foot wind tunnel at NASA Ames Research Center. The prior UAE literature was focused on model validations and not comparison between upwind/downwind. For example, Coton, Wang, and Galbraith [6] report on modeling (prescribed wake) for the downwind cases in the UAE Phase VI data. They found that the modeling results were highly dependent on the wake model, which included a wake width and velocity deficit. They also report on a phase difference between the measurements and the modeling, which was suspected to be a rotor-tower wake interaction. This seemed to be confirmed in the modeling results (RANS) of Zahle, Sørensen, and Johansen [7].

Experimental comparisons between upwind and downwind operation have been rare. Glasgow, Miller, and Corrigan [1] report on upwind and downwind operation of the MOD-0. Mean blade bending moments were found to be the same, but cyclic moment showed an increasing trend with wind speed for downwind operation. Power measurements were not available for this experiment. Yoshida [8] reports on a 100 kW turbine configured for upwind and

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downwind operation. Power was increased 7-10% in downwind operation, which was attributed to a favorable combination of sloping terrain and shaft tilt.

This paper addresses power and load differences between upwind and downwind operation, in addition to potential benefits from a tower aerodynamic shroud. Tower wake measurements, with and without the shroud, will also be presented and compared to previous research. Previous research on tower wakes were from wind tunnel studies by Snyder and Wentz [9] and Powles [10]. While Powles studied the wake of a 12-sided polygon, Snyder and Wentz also studied the polygon in addition to a cylinder and a cylinder with strakes. Wilmshurst, Powles, and Wilson [11] added an aerodynamic shroud to the tower in further work.

2. Methods

The NREL Unsteady Aerodynamics Experiment Phase VI wind turbine was 2-bladed with a 10 meter diameter (Figure 1). The NREL Unsteady Aerodynamics Experiment was conducted at the NASA-Ames 24.4- by 36.6-m (80- by 120-foot) wind tunnel. The tunnel is the largest in the world and the error due to blockage from the turbine was determined to be less than 2% for all conditions [5]. The turbine could be operated in upwind or downwind mode, with adjustable blade coning. For the results presented in this paper, the coning was 0° for upwind operation and 3.4° (downwind) for downwind operation. The teeter degree-of-freedom was fixed for upwind operation and free for downwind operation. The blades were kept at constant pitch and the rotor was maintained at constant 72 rpm and therefore the power was regulated by blade stall. Most of the comparisons in this paper are made at wind speeds below rated to avoid the complication of blade stall. Turbine and tunnel data was acquired at 521 Hz and most data points represent 30 seconds of data (36 rotor revolutions). Blade loads were obtained with strain gage bridges which were calibrated in the tunnel. Tower wake data was acquired by positioning the blade instrumented with five-hole pitot-tube probes downstream of the tower (Figure 2). Both blade loads and tower wake data was obtained with and without a tower aerodynamic shroud installed to investigate mitigating adverse effects of the tower wake. The tower diameter was 0.4064 m. The maximum thickness of the shroud was 0.46 m with a 0.89 m chord length. Unfortunately the details of the the shroud airfoil cross-section are missing.

Figure 1: UAE in upwind configuration. NASA image.

Figure 2: Tower shroud with instrumented blade positioned downwind for wake measurements. Photo by Lee Fingersh, NREL 36813

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Table 1 lists the test sequences that were used in this study. Further details of the test campaign are available in Reference [5].

Table 1: UAE test sequences.

Sequence	Description
B	Downwind operation
H	Upwind operation
3	Tower wake measurements
6	Tower shroud measurements
7	Downwind operation with shroud

3. Results and Discussion

With downwind operating at 3.4° coning, one would expect a lower power due to reduced rotor swept-area (0.35%) and loss due to tower shadow. However, Figure 3 does not show evidence of lower power for the downwind operation, except at the highest wind speed on the plot (9.3 m/s), just below rated power. Figure 4 shows a comparison of spanwise aerodynamic behavior between the upwind and downwind operation at 5 m/s. Downwind torque coefficient is higher inboard compared to upwind, as shown in Figure 4a. Downwind also shows higher inboard normal force (Figure 4b) and tangential force coefficient (Figure 4c). Surprisingly, the local angle of attack is lower for downwind as shown in Figure 4d. The spanwise angle is higher for the downwind case as shown in Figure 4e. The pressure coefficient (c_p) at the 30% station and 0° azimuth (Figure 4f) shows a higher suction peak for downwind operation, which explains the higher coefficients for downwind operation. The pressure side of the airfoil shows the same c_p for downwind and upwind. The cause of the higher suction peak has not been determined, but three-dimensional effects in the inboard sections are suspected. Upwind operation is affected by the wake from the rotating instrument package (see Figure 1), whereas downwind operation is affected by the nacelle wake.

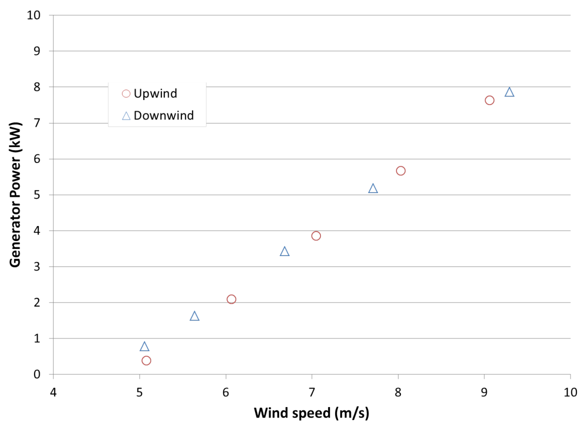


Figure 3: Average power for upwind and downwind operation. Downwind coning is 3.4°.

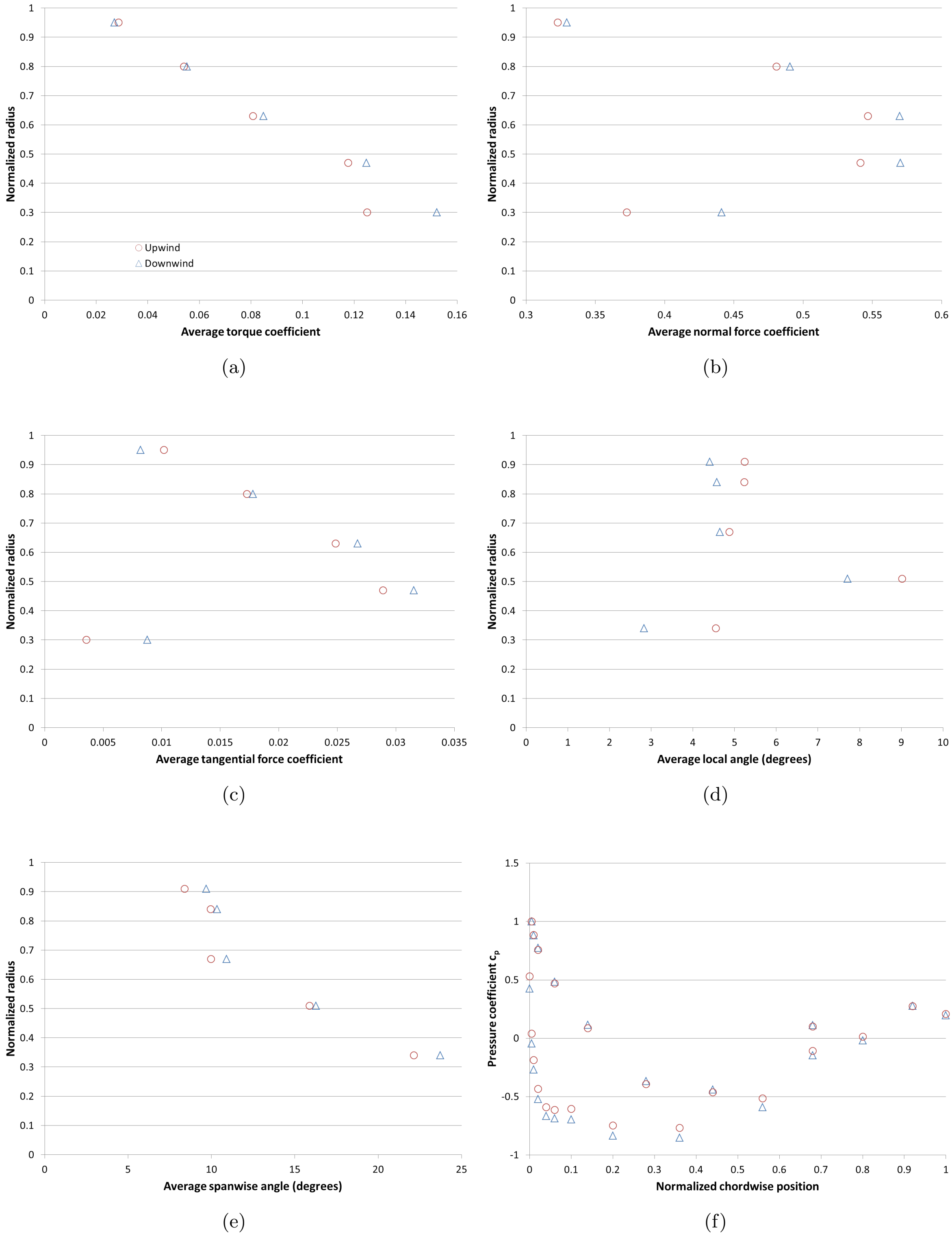


Figure 4: Average torque coefficient (a), normal force coefficient (b), tangential force coefficient (c), local flow angle (d), and spanwise flow angle (e) versus normalized radial position at 5 m/s tunnel speed along with averaged pressure coefficient at 30% station and 0° azimuth (f) versus normalized chord position

Figure 5 shows the difference in average flap bending moment for upwind and downwind operation. The downwind-coned rotor has a tendency to become unconed which produces a flap bending moment opposing the moment from aerodynamic loads. The predicted difference due to coning is 1040 N·m, which compares very well with the measurements. With this setting of downwind coning, the moment becomes negative at low wind wind speeds. Blade fatigue is shown in Figure 6, with the damage equivalent load (DEL) for upwind and downwind operation, including downwind with shroud. Results are shown in the region below stall operation of the turbine. In this region compared to upwind operation, blade fatigue is increased for downwind operation (e.g. 50% increase in DEL at 7 m/s). Use of a tower shroud results in significant reduction in fatigue; however, fatigue loads increase at higher wind speeds with a 10° misalignment. Here, misalignment is defined as the angle between the freestream velocity and mean chordline of the symmetrical shroud.

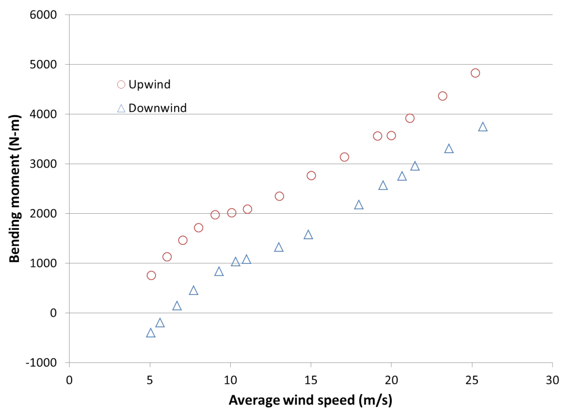


Figure 5: Average Blade 1 root flap bending moment for upwind and downwind operation.

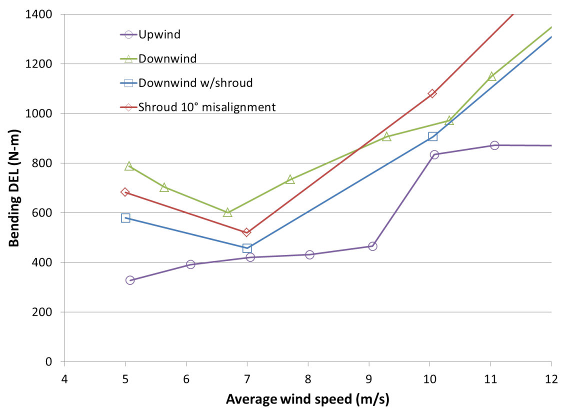
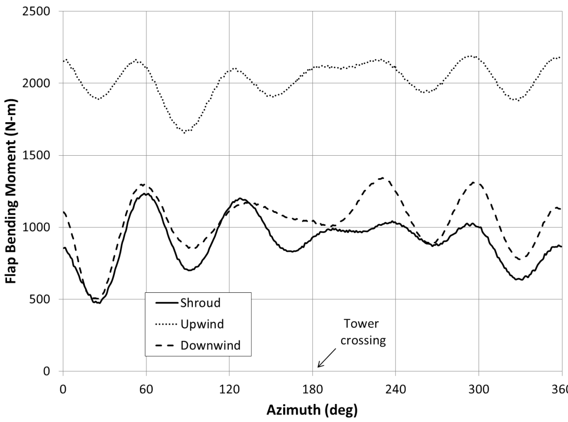


Figure 6: Blade 1 root flap bending moment damage equivalent load (DEL) for upwind, downwind, downwind with shroud, and shroud with 10° misalignment

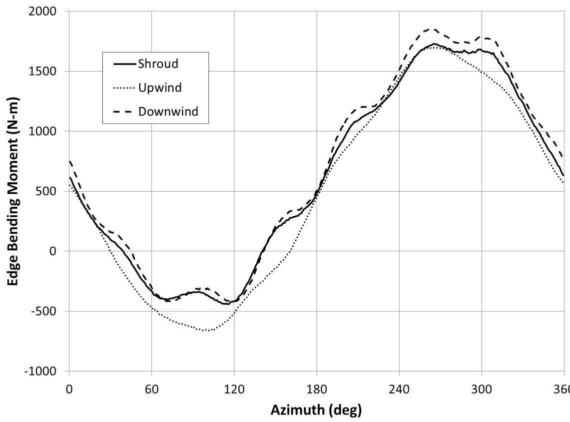
Figure 7 shows the azimuth averaged Blade 1 root flap and edge bending moments at a 10 m/s wind speed and 0° misalignment. The moments have been averaged over 36 revolutions. The blade response is periodic for the loads and configurations shown. The difference in average flap moment due to coning is clear in Figure 7a. The edge moments for downwind operation show higher harmonics in Figure 7b compared to the upwind trace, which primarily shows once-per-revolution variation due to the weight vector. The edge loads clearly show periodic excitation from interaction with the tower/shroud wake. The shroud does appear to reduce the magnitude of this wake induced mode.

One of the turbine blades was instrumented with five-hole probes to measure upstream dynamic pressure and flow angle. This blade was fixed in position downwind of the tower to obtain wake measurements. Figure 8 shows the wake velocity normalized to tunnel velocity at three tower diameters downwind and at 7 m/s wind speed. The Reynolds number for this condition is subcritical in the long-established experimental results for cylinder drag. Above this Reynolds number the transition point moves aft and the drag coefficient lowers significantly. A typical $\cos^2$ tower wake model from the literature [10] is shown as well for comparison. The comparison is good; however, this model requires knowledge of the maximum wake deficit and width, which for this condition was 0.35 with a total wake width of two-diameters.

Figure 9a shows the tower wake velocity normalized to tunnel velocity at 7, 15, and 20 m/s wind speeds. Figure 9b shows at the same speeds the turbulence intensity, defined as



(a)



(b)

Figure 7: Azimuth averaged Blade 1 root flap (a) and edge (b) moments at 10 m/s wind speed

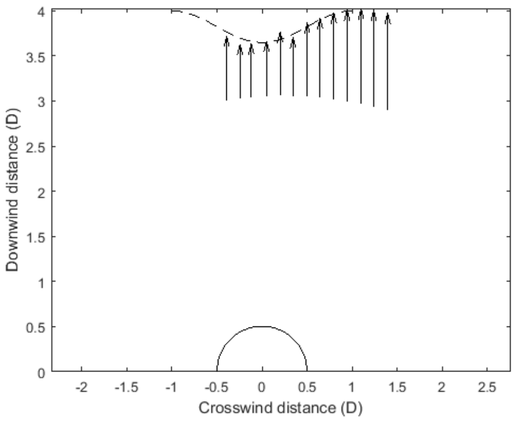
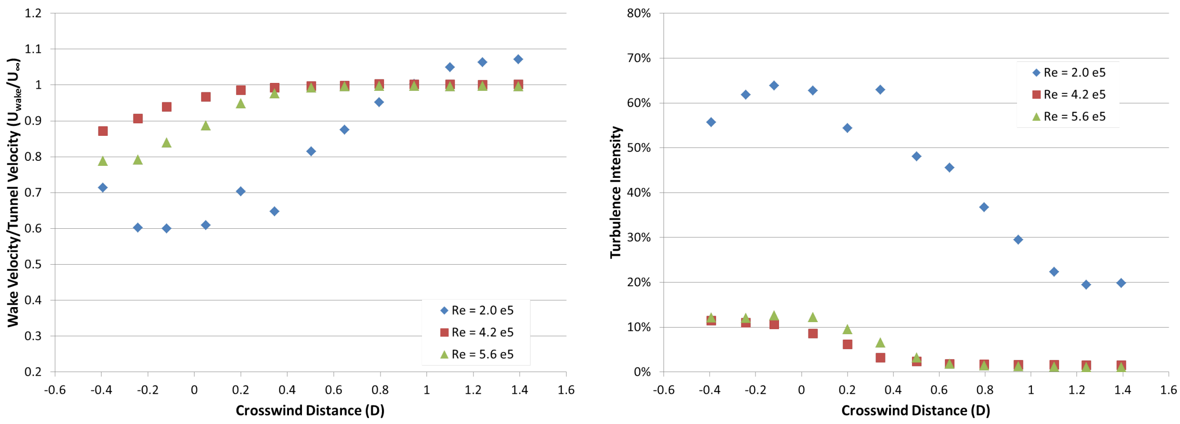


Figure 8: Average wake velocity normalized by tunnel velocity (arrows), with $\cos^2$ (– – –) wake model. 7 m/s, $Re_D = 1.95 \times 10^5$. Vectors at the far right are at 1.00. Vector bases are not at same downwind distance due to measurement method.

the standard deviation of the wake velocity divided by the average tunnel velocity. These speeds represent subcritical, transitional, and supercritical Reynolds numbers for the cylinder wake. The wake deficit and turbulence intensity reduces with Reynolds number and becomes asymmetric. The subcritical wake also shows a double peak in the turbulence intensity. These behaviors were similarly observed in experiments of cylinder wakes by Snyder and Wentz [9]. The double peak was attributed to areas of high mixing in the subcritical wake. The asymmetry was attributed to turbulent separation on one side of the cylinder and laminar separation on the other side. The asymmetry might also explain the azimuthal offset found in downwind modeling by Coton, Wang, and Galbraith [6]. Note that for modern MW-scale turbines, the tower Reynolds number would most likely be supercritical at all operational wind speeds.

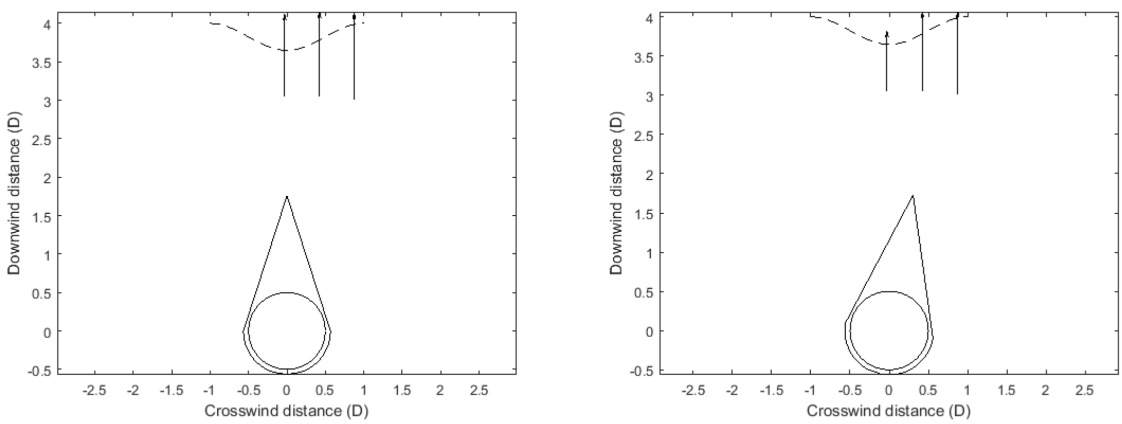
Figure 10 shows wake measurements at 7 m/s with the shroud installed. The $\cos^2$ wake model from Figure 8 is included for comparison. Figure 10a shows the wake with the shroud aligned with the freestream. The average velocity in the wake is actually higher than the freestream (arrow length greater than 1) where the measurements were taken. Figure 10b shows the shroud misaligned 10° from the freestream. The wake in this condition is showing a velocity reduction; however, not as high as the tower-only wake.

Figure 11a shows the shroud wake velocity normalized to tunnel velocity at 7, 15, and 20 m/s wind speeds. Figure 11b shows at the same speeds the turbulence intensity for 0° shroud misalignment. The wake deficit increases slightly with Reynolds number, and seems to be of



(a) (b)

Figure 9: Tower wake normalized velocity (a) and turbulence intensity (b) at Reynolds numbers corresponding to 7, 15, and 20 m/s



(a) (b)

Figure 10: Measured normalized wake velocity at 7 m/s with tower shroud at 0° (a) and 10° misalignment (b) with $\cos^2$ $(---)$ model from Fig. 8. $Re_c = 4.26 \times 10^5$. Vectors at the far right in (a) is at 1.12. Vector bases are not at same downwind distance due to measurement method.

smaller width compared to the bare tower wake. These same findings were found in experiments with a tower shroud by Wilmshurst, Powles, and Wilson [11]. The turbulence intensity is much lower than the un-shrouded tower wake shown in Figure 9b. In summary, the shroud wake is narrower and more steady than the bare tower which has a wider, more fluctuating wake. These results can explain the much lower damage equivalent load in Figure 6 with the shroud installed. Note that tower strakes, tower tapering, or lattice towers could also reduce the tower wake.

Figures 11c, 11d, 11e and 11f shows the tower wake velocity normalized to tunnel velocity and turbulence intensity at 7, 15, and 20 m/s wind speeds for ±10° shroud misalignment. With the misalignment the wake velocity decreases and turbulence intensity increases dramatically which results in the increased damage equivalent load shown in Figure 6.

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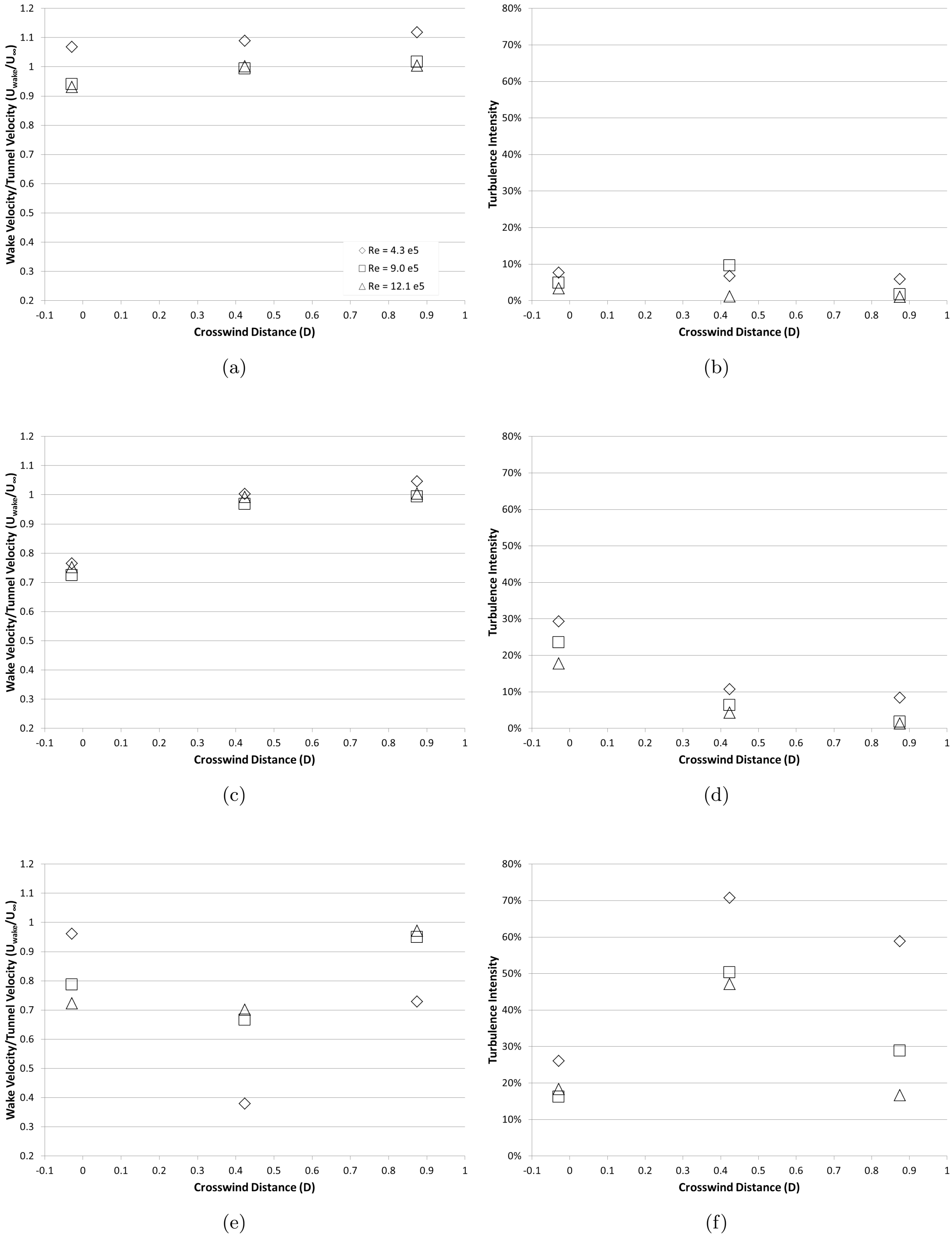

Figure 11: Shroud wake normalized velocity (left) and turbulence intensity (right) at chord Reynolds numbers corresponding to 7, 15, and 20 m/s for 0° (a and b), +10° (c and d) and −10° (e and f) shroud misalignment

4. Conclusions

The comparison between upwind and downwind operation of NREL's Phase VI Unsteady Aerodynamics Experiment show that downwind operation should be reconsidered for future large wind turbines. Downwind coning offers a significant and predictable reduction in average loads for blade flap-bending, in comparison to upwind operation, and does not seem to result in lower energy capture.

The expected increased fatigue loads from downwind operation compared to upwind operation was confirmed in the experiment. The loads are the result of the tower wake, which was measured in this experiment and compare well with previous wake studies. The wake is dependent on the Reynolds numbers encountered in this study. However, the higher, supercritical Reynolds numbers and fully turbulent wakes for large modern turbines may remove this dependency.

The fatigue loads in tower wake operation can be mitigated significantly with an aerodynamic shroud. However, the shroud must remain aligned with the wind direction, as the results show fatigue loads returning to tower-alone levels with a 10° misalignment. Further research may demonstrate if a shroud will lower the noise generation.

Acknowledgments

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