Structure of yawed wind turbine wakes in thermally neutral and stable boundary layers

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1 ABSTRACT

To investigate variation in the wake structure behind a yawed wind turbine model in different thermal boundary layers, experiments were performed in the Environmental Flow Research Centre (EnFlo) at the University of Surrey. These utilised the 20x3.5x1.5m^3 working section Meteorological Tunnel, which can produce boundary layers of different thermal stabilities. The deep boundary layer used for these experiments had a depth (δ) to turbine hub height (z_{hub} = 300mm) ratio of $\delta/z_{hub} \approx 2$ for the neutral and stable flows, with a bulk Richardson number of $Ri_b \approx 0.2$ and surface Obukhov length $L_{surface} \approx$ 1m in the stable case. The turbine was run in these layers at yaw angles of -20 °,0 °, and 20° at a tip-speed ratio of 6. Velocity measurements were taken behind this model using a 3D Laser Doppler Anemometry (LDA) system. This allowed both the time-mean and fluctuating components of the velocity to be captured in the streamwise, lateral, and vertical directions. The measured data sets comprise lateral profiles behind the turbine at z_{hub}, and vertical profiles along the centreline (y = 0), at a series of downstream distances.

The influence of thermal stability on the wake is evaluated across several quantities. First, a reduction of wake growth in stable flows is observed, along with an anti-axisymmetric wake shape. Second, wake recovery is shown to be hindered by stable conditions. Next, yaw is considered by comparing the rotor area averaged velocity across the 6 test cases, showing that a positive yaw performs best. Finally, lateral wake deflection is determined to demonstrate the larger deflections produced by a positive yaw angle.

2 INTRODUCTION

With the onset of climate change a global transition towards clean energy sources is underway. In the UK wind energy is identified as a key contributor towards this, with wind farms expected to produce 50GW of power annually by 2030, half of all renewable production [1]. For this to be achieved not only is new infrastructure of wind farms and power distribution needed, but existing wind farms should be made more efficient. Presently, a key limitation to production is the waking of downstream turbines within a farm, starving downstream turbines and limiting their power output. A promising method to overcome this is yaw control, where the upstream turbine's wake is redirected away from a downstream turbine to both increase the overall power yield and decrease the fatigue loading from wake turbulence. Studies on yaw strategies suggest an increase of 10% in farm power output is possible [2], but to be implemented in practice wake modelling and experimental data are required across a wide range of conditions. Research on yawed turbines has mostly focused on a simplified 2D wake in the lateral plane. Building upon established models of un-yawed turbines that represent the wake velocity deficit as a series of Gaussian curves [3]. However, behind a yawed turbine the formation of the counter-rotating vortex pair (CVP) will distort the wake from an ellipse to a "kidney" shape. Here, the lateral profile will remain in its established Gaussian form, but the vertical profile will not, forming two peaks as it effectively crosses the curled wake twice. Thus, to properly predict the power available to a downwind turbine and the effectiveness of yaw an improved understanding of this vertical plane is needed.

Along with yaw, the experiments herein also consider the impact of thermal stability on the wake. The relationship between stability and wake development is well established; in increasingly stable flows the turbulence intensity is reduced, hindering wake entrainment and slowing the wake's growth and recovery [4]. However, less work has been performed on the impact of stability on yaw, with initial research suggesting that yaw effectiveness can increase in stable flows [5] it is crucial to better quantify how this can be exploited to maximise wind farm efficiency.

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3 EXPERIMENTAL METHODOLOGY

Experiments were undertaken in the Meteorological tunnel at the EnFlo centre. Here, boundary layers of varying thermal stability are generated by a set of heaters that apply a temperature profile at the flow inlet, alongside a series of cooling/heating panels on the floor that maintain the positive/negative thermal gradient. For more detail on how these are used to produce different levels of stability see [6]. Roughness length is controlled by blocks on the floor acting as roughness elements. Boundary layer growth is accelerated by 12 Irwin spires at the front of the working section, each measuring 600mm in height. These ensure the flow is fully developed before it reaches the turbine 10m downstream. A flow speed, $U_{\infty,hub}$, of 1.5ms^{-1} was set for both boundary layers, with upwind flow speed recorded using a sonic anemometer at the tunnel inlet. The resulting chord Reynolds number was around 3x10^5, high enough for Reynolds effects to be somewhat mitigated and comparisons to a full-scale turbine to be possible. Cases for the two stabilities with the varying turbine configurations are outlined in table 1.

The wind turbine used, shown in figure 1a, was of 0.416m diameter with a hub height of 0.3m. Further details of its design can be found in [6]. The turbine was run at a tip speed ratio of 6. For each boundary layer the required RPM was calculated from the mean of the velocity at z_{hub} in an empty tunnel. In the yawed cases a positive angle indicates where the effects of yaw and turbine rotation combine to give a larger wake deflection. Here, this results from a clockwise rotation of the turbine viewed from the front and anti-clockwise yaw angle viewed from above. The turbine's RPM was monitored by a photo-Darlington sensor mounted to the hub, this showed the variation of the RPM to be within $\pm$0.25%.

Wake measurements were taken using LDA, giving both time averages and fluctuations of velocity in the x, y, z directions to determine the values of U, u', V, v', W, w'. Flow seeding was provided by evaporated sugar water, with the level of seeding controlled to give a minimum data rate of 100Hz. Each measurement lasted 3 minutes to ensure that the fluctuating components were accurately captured. Measurements were taken at downstream distances of x/D = 2, 2.7, 5, 6, 8, 10.8, 15.4 to give a good range of data for both the near and far wake. Vertical profile measurements were made between a height of 50mm and 750mm along y = 0. Lateral profiles covered a range between $\pm$810mm at z_{hub}. Each had a spacing of around 20mm. The profiles are illustrated in figure 1b.

Table 1. Overview of setups for which data was taken.

Flow \ Turbine	-20	0	20	None
Neutral	*Case -20N*	*Case 0N*	*Case 20N*	*Case Empty N*
Stable	*Case -20S*	*Case 0S*	*Case 20S*	*Case Empty S*

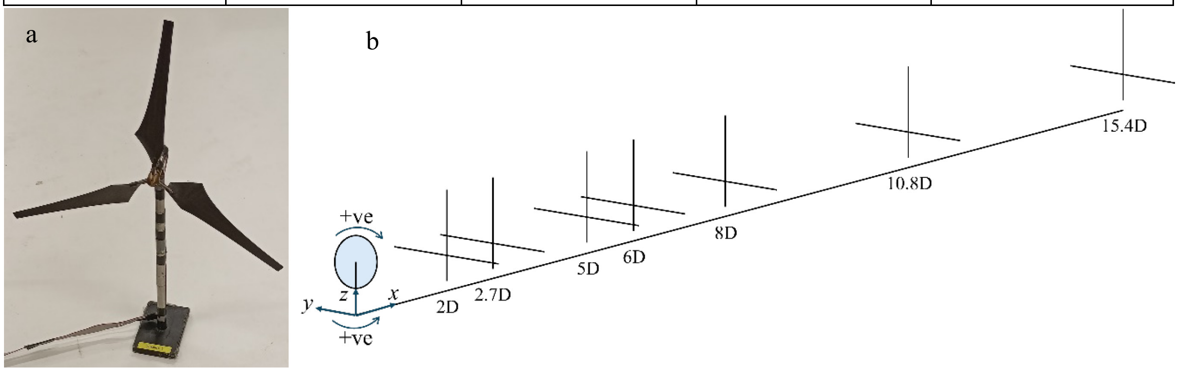

Figure 1. a. Wind tunnel model used for the experiments. b. LDA measurement profile locations.

4 RESULTS

Figure 2a shows the vertical profiles of wake velocity normalised by local free stream velocity, U_{fs}, in the neutral case, with the velocity tending back towards the inflow profile, illustrated in black. Initially, the wake consists of two peaks, due to the turbine acting as an annular disk and not slowing the flow as much near the hub. Downstream, wake mixing blends these peaks into the familiar single peak. For this data set the transition occurs around 6-8D downstream, thus, figure 2b shows the Gaussian curve fitted to velocity deficit from 8D onwards. This deficit has been corrected according to the local free stream velocity, as the turbine's blockage slightly accelerates the flow.

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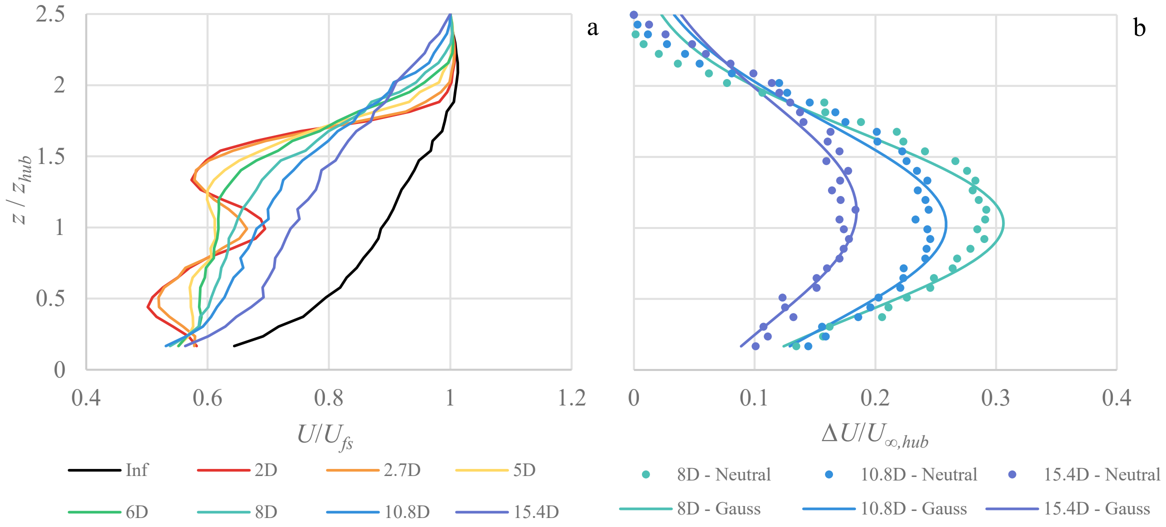

Figure 2. a, Wake velocity of the un-yawed turbine in 0N. b, Corresponding corrected velocity deficits with fitted Gaussian curves.

The same curves were fitted for the lateral profiles of the un-yawed configuration. Each curve giving a wake width and maximum velocity deficit. However, the wake will shift from the hub centre due to both wake meandering and yaw so the profiles measured here will be slight underestimates of the true wake maximum. To correct for this the wake is assumed to be elliptical with zero tilt, as the vertical and lateral profiles are found to suitably overlap at the hub centreline. As such, the width and height of the ellipse can be determined using the standard deviations of the vertical/lateral Gaussian curves to find four non-mirrored points on the ellipse. These are shown in figure 3a. Finally, the true maximum velocity deficit is found from the measured velocity at the curves' overlap point along the hub centreline and the equation of a bi-variate Gaussian distribution. This is shown in figure 3b. As expected, the velocity recovers slower in the stable case, with both cases following a power law relationship.

Figure 3a demonstrates that in neutral flow the vertical and lateral growth behaves roughly the same, so traditional modelling methods are appropriate here. However, in the stable case there is a deviation between the two, with the wake growing faster vertically than laterally, illustrating the need for more refined vertical modelling.

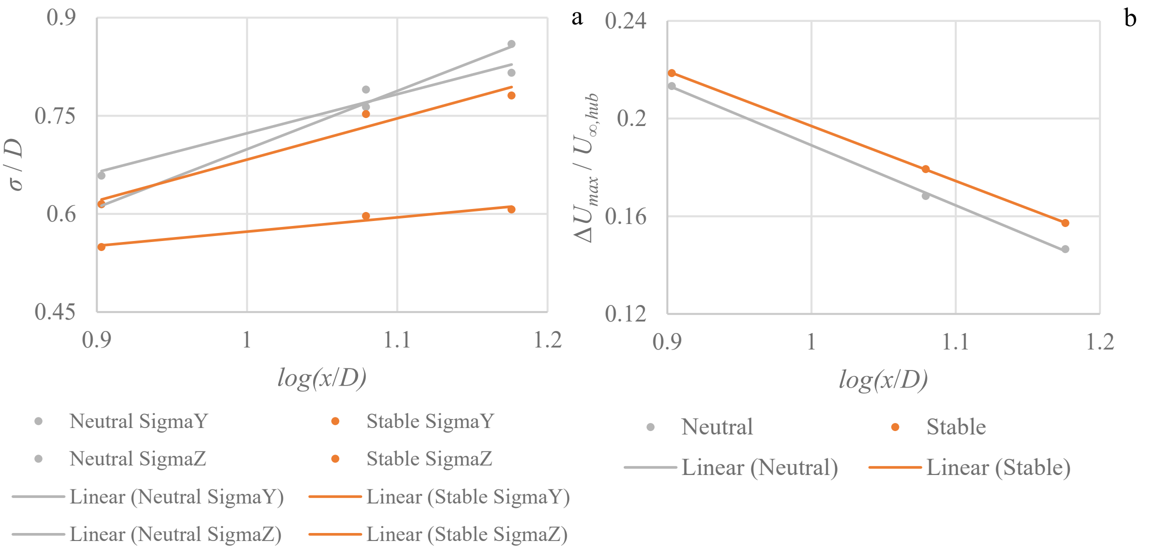

Figure 3. a, Comparison of the corrected wake growth in the two directions across 0N and 0S. b, Recovery of the corrected maximum velocity deficit.

The same approach cannot readily be used for the yawed data, as the CVP distorts the vertical profiles into having two peaks. Instead, comparisons are made by averaging wake velocity across the diameter of a virtual downstream turbine. This is shown for the six cases in figure 4a. For each turbine orientation

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the flow recovers faster in the neutral than in the stable case, again as expected. The benefits of yaw can also be clearly seen here; in both flows wake velocity increases when the turbine is negatively yawed, with a further increase for positive yaw, signifying a higher wind resource is available for downstream turbines in these yawed cases. The wake deflection away from the virtual downwind turbine providing this performance increase is shown in 5b, showing that deflection is maximised in the stable case for a negative yaw, while for a positive yaw the neutral flow gives a slightly higher deflection; it is as yet unclear why this is the case, requiring further scrutiny.

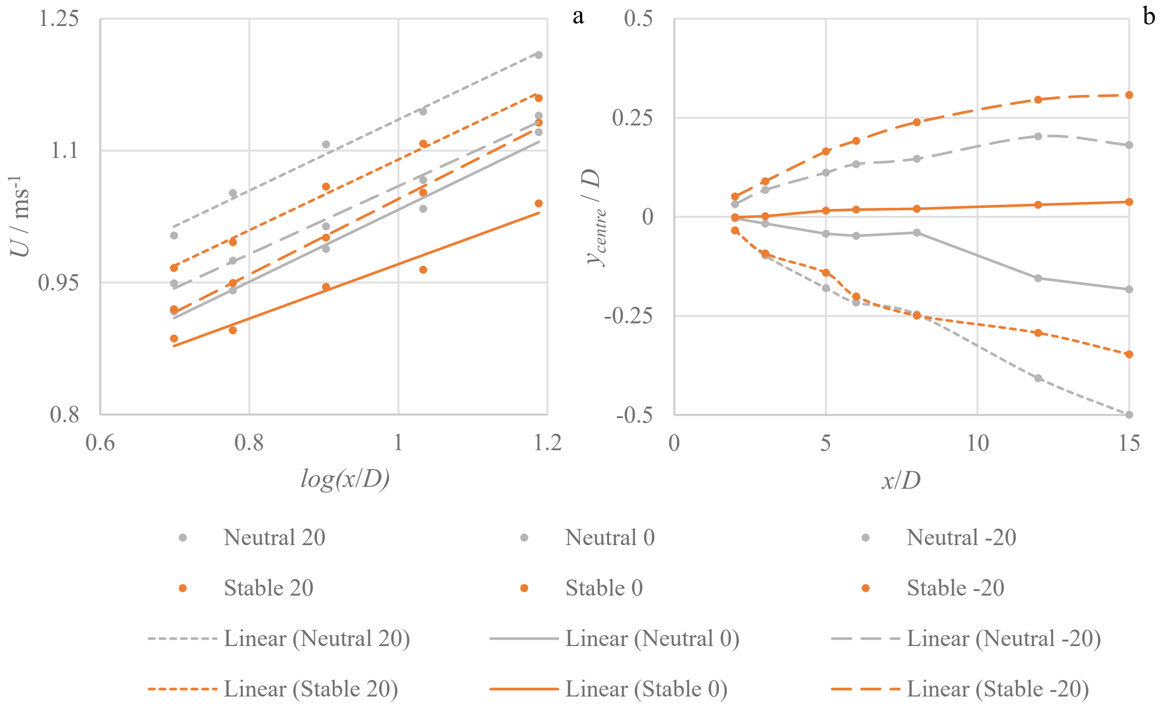

Figure 4. a, Disk area mass-flow averaged velocity in the vertical profile for the three yaw directions in stable and neutral flow. b, Lateral centres of the six cases.

5 CONCLUSIONS

The presented data demonstrates the differences that arise between vertical and lateral wake profiles in different flow stabilities and yaw directions, illustrating the need for alternative modelling approaches to wake flows in the vertical plane. The potential benefits of yaw on wind farm production are explored, highlighting the most effective configurations. Reflecting upon the results of the experiment, the approaches needed for future modelling work are discussed.

6 REFERENCES

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