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Characterizing Tilt Effects on Wind Plants

by

Ryan Scott

A thesis submitted in partial fulfilment of the
requirements for the degree of

Master of Science
in
Mechanical Engineering

Thesis Committee:
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Portland State University
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Abstract

Tilting the nacelle of a wind turbine modifies entrainment into the wind plant and impacts total efficiency. Extreme angles can produce flying and crashing wakes where the wake either disrupts entrainment from the undisturbed flow above or is decimated on the ground. The effect of tilt angle on downstream wake behavior was investigated in a series of wind tunnel experiments. Scale model turbines with a hub height and diameter of 12 cm were arranged in a Cartesian array comprised of four rows of three turbines each. Nacelle tilt was varied in the third row from -15° to 15° in chosen 5° increments. Stereo PIV measurements of the instantaneous velocity field were recorded at four locations for each angle. Tilted wakes are described in terms of the average streamwise velocity field, wall-normal velocity field, Reynolds stresses, and mean vertical transport of kinetic energy. Conditional sampling is used to quantify the importance of sweep vs. ejection events and thus downwards vs. upwards momentum transfer. Additionally, wake center displacement and changes in net power are presented and compared to existing models. The results demonstrate large variations in wake velocity and vertical displacement with enhanced vertical energy and momentum transfer for negative tilt angles. Simulation models accurately predict wake deflection while analytic models deviate considerably highlighting the difficulties in describing tilt phenomena. Negative angles successfully produce crashing wakes and improve the availability of kinetic energy thereby improving the power output of the wind plant.

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1 Introduction

Wind energy continues to grow as a source of energy production. Wind plants and individual turbines have increased in both scale and power output [28, 8]. Despite these advancements, wind plants often operate below their design efficiency [3]. Turbine wakes are understood to act as a primary source of inefficiency in wind plants [1]. Although terrestrial and offshore wind plants operate in different conditions, they are both affected by wakes impinging upon other turbines. Therefore, mitigating the effects of turbine wakes is a central component of increasing wind global energy production.

Various methods have been developed to reduce the adverse effects of wakes on wind plant production. Variations in turbine arrangement to avoid wakes within wind plants have been proposed and successfully demonstrated increased performance [17, 9, 12]. Regardless of turbine arrangement, Reynolds shear stresses achieve a maximum within the first rows of a wind plant reducing the effectiveness of staggered arrangements for large arrays [17, 12]. Due to the static nature of wind plants, this implementation is restricted to new installations. Counter-rotating rotors have shown improvements in individual and total wind plant efficiency [16]. While this approach is not strictly confined to new installations, retrofitting existing arrays would pose substantial costs.

Wake deflection has gained popularity as a method of improving performance for both new and existing wind plants. Although individual turbines lose efficiency in non-orthogonal flows [5], the benefits of wake deflection have been shown to increase net efficiency across the wind plant [11, 7]. Horizontal or yaw deflection is an attractive option as it can take advantage of existing infrastructure [23]. Yaw deflection has been widely studied in experiment, simulation, and full scale implementation [19, 5,

7, 11, 20, 13, 23].

Yaw deflection has been found to improve net performance and reduce turbine loadings [11, 22]. The actuator line model has been well adopted to model the effects of turbine wakes [26, 27]. It has been successfully extended to describe the effects of turbine wake deflection [19, 13]. This model does not, however, account for the curled shape of a yawed wake where the wake center deflects further laterally than the top and bottom tips [19]. These effects are observed regardless of inflow conditions and individual turbine characteristics [4, 25]. Recent energy budget models have been developed to include asymmetric wake distributions in the far wake region and successfully predicted yawed turbine performance [6]. Even with recent improvements, unexpected and disadvantageous scenarios have been reported for full-scale implementation of active yaw control in a wind plant [23].

Vertical or tilt deflection has not received the extensive coverage of yaw deflection. This is partly due to the lack of turbine infrastructure capable of supporting tilt control [13]. Yet, offshore wind plants with floating turbines constantly experience tilt deflection due to wave motion. Oscillating vertical wake displacement was found to reduce fatigue loads and turbulent mixing [24]. Because wake deflection occurs vertically, interactions with the atmospheric boundary layer are non-trivial. This leads to differences in wake dynamics for upwards and downwards deflection with measured differences in Reynolds stresses and turbulence production for the top tip and bottom tip between fixed and oscillating turbines [24]. Extreme angles can produce ‘flying’ and ‘crashing’ wakes where the wake either disrupts entrainment from the undisturbed flow above or is decimated on the ground. For wind plant settings, directing a wake downwards is preferable but produce new challenges in turbine design to prevent mast strikes or losses from mast-rotor interactions [13, 14]. Models have been proposed to estimate the effects of tilt deflection in a wind plant setting and on

an individual turbine [13, 15]. Tilt deflection was found to translate wake centers in simulation, however, the extent and effectiveness of vertical displacement are a topic of debate [15]. Tilt deflection was found to be capable of accessing high-altitude, high-speed winds from the atmospheric boundary layer and increasing wind plant performance [2, 13, 14]. This behavior provides tilt control a unique advantage over other methods which has not been otherwise discussed in the literature. Moreover, the lack of emphasis on tilt deflection has created an absence of experimental data for model validation. A parametric study of tilt deflection in a wind plant setting has not yet been conducted outside of simulations.

Here, tilt deflection is considered as a method to improve efficiency for both terrestrial and offshore wind plants. Positive and negative tilt angles are evaluated in wind tunnel experiment with a Cartesian array of model turbines for full consideration on the effects of tilt angle on wake behavior and wind plant performance. Details concerning the experimental setup are provided in Section 3. Results and discussion follow in Section 4. First, changes in wake dynamics stemming from turbine tilt are quantified through the mean velocity and Reynolds stresses. Tilt induced variations in the flux of kinetic energy and vertical momentum are considered next to evaluate the role of tilt in determining wake recovery and entrainment. Additional insight on the effects of tilt on the vertical flux of kinetic energy is gained by employing conditional sampling. Finally, wake center displacements and differences in net plant power are compared to simulations and analytic models from the literature. Concluding remarks are presented thereafter in Section 5.

2 Theory

The Reynolds averaged Navier-Stokes equation including the streamwise turbine thrust force f is introduced in tensor notation as

$$U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} - \frac{\partial \overline{u'_i u'_j}}{\partial x_j} - f_i \quad (1)$$

In this and subsequent formulations, mean quantities are expressed as upper case (i.e., U) with fluctuations about the mean as lower case primed, (i.e., u') following the Reynolds decomposition. Subscript indices denote the streamwise (U), wall-normal (V), and spanwise (W) velocity components in x , y , and z , respectively. Time-average is depicted with an overline. Moreover, ρ is the fluid density and P represents the mean pressure. Terms relating to viscous dissipation and diffusion as well as unsteadiness have been neglected as all measurements in the present work are recorded sufficiently far from wall interactions. By taking the scalar product of Equation 1 with the average velocity and contracting free indices, the equation mean kinetic energy in the flow is written as

$$\underbrace{U_j \frac{\partial \frac{1}{2} U_i^2}{\partial x_j}}_{\text{I}} = -\underbrace{\frac{1}{\rho} U_i \frac{\partial P}{\partial x_i}}_{\text{II}} - \underbrace{\frac{\partial U_i \overline{u'_i u'_j}}{\partial x_j}}_{\text{III}} + \underbrace{\overline{u'_i u'_j} \frac{\partial U_i}{\partial x_j}}_{\text{IV}} - \mathcal{F}_T \quad (2)$$

The convection of mean kinetic energy (I) is balanced by terms for energy added by the mean pressure gradient (II), mean kinetic energy flux (III), the production of turbulence kinetic energy (IV), and the turbine power extraction $\mathcal{F}_T$. Because tilt acts on wake behavior in the vertical direction, the mean transport of kinetic energy from (III) is of particular interest. Furthermore, turbine power extraction varies with tilt angle and as such power extraction must be considered independently for each

tilt angle. The power extracted by the turbine can be measured by recording voltage at a known resistance

$$\mathcal{F}_T = P = \frac{V^2}{R} \quad (3)$$

Conditional sampling was employed to quantify the importance of sweep and ejection events following [21]. The formalism for conditional sampling derives from categorizing the sign of the turbulent fluctuations into four quadrants (Fig. 1) and is written as

$$\overline{u'v'_k} = \frac{1}{N} \sum_{n=1}^N I_k[u'_n(x, y); v'_n(x, y)] u'_n(x, y) v'_n(x, y), \quad i \neq j \quad (4)$$

where $I_k = 1$ and $k = 1, 2, 3, 4$ such that the total Reynolds stresses are described by

$$\overline{u'v'} = \sum_{k=1}^4 \overline{u'v'_k} \quad (5)$$

The normalized stress fraction is defined by

$$S_k = \frac{\overline{u'v'_k}}{(\overline{u'^2 v'^2})^{1/2}}, \quad k = 1, 2, 3, 4 \quad (6)$$

From the normalized stress fraction, the relative dominance of sweep to ejection events can be described by a single parameter ΔS_0 from

$$\Delta S_0 = S_4 - S_2 \quad (7)$$

Figure 1: *Conditional sampling categories organized by sign.*

Analytic wake deflection models based on two different formulations are introduced for comparison to experimental results. Wake deflection for a yawed turbine is considered to evaluate the effectiveness of transferring the well-defined body of literature on yawed turbines to estimate wake behavior from a tilted turbine. The model for wake center displacement of a turbine in yaw [19] is defined as:

$$\frac{y_c(x)}{D} = \cos^2(\theta) \sin(\theta) \frac{C_T}{2\beta} \left(1 - \frac{1}{\beta x/D + 1} \right) \quad (8)$$

where C_T is the thrust coefficient, β is the wake expansion parameter, and θ is the yaw angle, implemented as tilt angle in the present work. A more direct comparison between model and experiment can be made to the empirical model presented in [15]. The empirical model for wake offset of a tilted turbine for low tilt angles is:

$$y(x) = 0.24x C_T \tan(\theta) \quad (9)$$

where C_T is again the thrust coefficient and θ is the tilt angle.

3 Experimental Setup

Wind Tunnel Facility

Experiments were performed in the closed-circuit wind tunnel at Portland State University (Fig. 2). The tunnel has a cross section of $1.2 \text{ m} \times 0.8 \text{ m}$ and a test section measuring 5 m . Additionally, the tunnel is equipped with an active grid consisting of 7 horizontal and 6 vertical rods to facilitate studies at varied turbulence intensities. For the present work, the grid was maintained in a passive state by positioning grid elements parallel to the incoming flow. Vertical strakes were employed in the entrance region to generate a boundary layer profile with similar characteristics to the atmospheric boundary layer. The strakes are manufactured of acrylic and are identical in geometry to those used by Hamilton and Cal [16]. Surface roughness was introduced by spacing a series of porous chains with an average diameter of 0.0075 m in increments of 0.11 m upstream of the turbine array following Hamilton *et al.* [17]. Hub-height inflow velocity was measured at the first turbine row via temperature compensated pitot tube and converged to 3.2 m/s .

Figure 2: *Portland State University wind tunnel with experimental apparatus and measurement locations to scale. The passive grid is shown for reference only and is not to scale; chains are shown at 2x scale to enhance visibility. All dimensions are in meters unless otherwise noted.*

Model Turbines

Scale model turbines with a hub height and diameter of 0.12 m were arranged in a Cartesian array comprised of four evenly spaced rows of three turbines each. Streamwise distance between turbine rows as $6D$ and wall-normal spacing was $3D$. Each turbine consists of a die-pressed rotor with a root twist of $\gamma = 22^\circ$ and a tip twist of $\gamma = 15^\circ$ with a thrust coefficient of 0.64 (3). Rotors are fixed to a DC motor (Faulhaber GMBH & Co., Series 1331T012SR) and loaded such that turbines operated at their peak power coefficient, C_P , as described by Hamilton and Cal [16]. Further descriptions of turbine design and operating characteristics including the thrust coefficient are described by Camp and Cal [10]. Nacelle tilt was varied in the third row from -15° to 15° in chosen 5° increments by means of a 3D printed adapter (4).

Instrumentation and Measurements

Measurements of the instantaneous velocity field were recorded with a LaVision stereo particle image velocimetry (SPIV) system. Images were recorded with two CCD cameras (LaVision 4MP Pro LX) fitted with Schiempflug adapters. The laser sheet was generated with a double pulsed Nd:YAG laser (Litron Nano L 200-15) and measured approximately 0.001 m across. Neutrally buoyant diethylhexyl sebacate droplets were introduced upstream of the test section and allowed to mix thoroughly. In addition to SPIV images, turbine voltages in the 3rd and 4th rows were recorded at 1 kHz (NI DAQ) for two 120s intervals.

2000 SPIV images were captured at four locations for each angle: immediately in front of the 3rd row, immediately behind the 3rd row, immediately in front of the 4th row, and immediately behind the 4th row. The measurement window spanned $2D$ and the streamwise spacing from the nearest turbine to the center of the measurement

Figure 3: *Technical drawing of the model wind turbines. The mounting plate spans the width of the tunnel although a segment is presented in the figure. All dimensions are in millimeters unless otherwise noted.*

window was $1.125D$. A two-level calibration plate of known size, position, and marker depth was used to calibrate the SPIV setup for each window. Self calibration was performed prior to each measurement in DaVis 8.4.0.

Raw images were processed in DaVis 8.4.0 using a multi-pass FFT algorithm. The interrogation window was reduced between passes from 24 px to 12 px resulting in a final resolution of 6 pixels corresponding to ~ 0.00075 m. The interrogation window was then truncated to remove turbine interference. Erroneous vectors representing less than 2% of the overall data were replaced with interpolated values from valid overlapping vectors.

Figure 4: *Range of considered nacelle tilt angles with corresponding 3D printed adapters. Nacelles were pivoted about the center of the mast. Mast clearance was verified before each test to prevent collisions.*

4 Results and Discussion

Average Velocity Fields

The influence of turbine tilt is shown in contours of the average streamwise velocity field U/U_∞ for $\theta = 15^\circ$, $\theta = 0^\circ$, and $\theta = -15^\circ$ (Fig. 5). By design, the inflow from previous turbines into the 3rd row is relatively uniform between values of θ . A lingering velocity deficit from upstream turbines is present at $y/D = -0.25$ and dissipates by $x/D = 1$ regardless of tilt angle. The streamwise velocity increases with elevation and high-altitude, high speed flow, is found from $y/D = 0.5$ extending beyond the measurement window. The measurement region does not include the turbine and as such does not capture local effects of turbine tilt on the inflow.

A wake region of reduced velocity is present behind the rotor from $y/D = -0.5$ to $y/D = 0.5$, as expected. Turbine tilt was modified in the 3rd row and the immediate downstream velocity field demonstrates distinct behaviors for each value of θ . The wake behind an unaltered turbine at $\theta = 0^\circ$ is typical in appearance with a moderate velocity deficit which recovers downstream. As the wake approaches $x/D = 2$, the velocity field is approaching the inflow condition and the wake center has dropped by $0.1D$. The influence of tilt on the wake is evidenced by differences in wake magnitude,

streamwise longevity, and elevation. For $\theta = 15^\circ$, the velocity deficit is the greatest in magnitude and spans the measurement window. Moreover, the wake is projected up into the boundary layer where it achieves a maximum vertical translation of $0.2D$ by $x/D = 2$. The wake deflection further displaced the undisturbed flow higher into the boundary layer. This behavior is congruent with the description of flying wakes which inhibit entrainment by disrupting the undisturbed flow above. Tilting the opposite direction to $\theta = -15^\circ$ results in the lowest observed velocity deficit and shortest wake lifetime. The velocity deficit has recovered by $x/D = 2$ and translated downwards by $0.2D$ at this distance. This suggests a relationship between tilt angle and the magnitude of the velocity deficit where negative tilt angles produce weaker wakes. This effect may also be present from the losses in turbine efficiency due to tilting the blades away from incoming high-speed flow and interactions with the turbine mast.

In front of the 4th row, the behaviors noted in the near wake have continued for each value of θ . For the unaltered turbine at $\theta = 0^\circ$, the velocity field closely resembles the inflow to the 3rd row. A weak wake is present near $y/D = -0.25$ which dissipates by $x/D = 1$. The flying wake created by $\theta = 15^\circ$ has fully recovered, however, the undisturbed flow remains above $y/D = 0.6$ in contrast to $y/D = 0.5$ for the inflow conditions. This is indicative of positively skewed wakes enduring beyond the initial velocity deficit and affecting the performance of subsequent turbine rows. For $\theta = -15^\circ$, the velocity deficit has fully recovered although the vertical velocity profile differs from other values of θ and the inflow to the 3rd row. The wake has evolved into a crashing wake with a low-velocity region present from $y/D = -0.2$ to the ground. As the crashing wake loses altitude approaching the 4th row, the undisturbed flow is pulled down to $y/D = 0.35$. Thus, negative tilt angles are observed to successfully draw high-speed flow from the boundary layer into subsequent turbine rows and improve net plant performance.

Behind the 4th row, differences in wake magnitude and vertical velocity profile remain between tilt angles. With $\theta = 0^\circ$, a second classical wake develops behind the rotor. This wake is lower in magnitude than the previous upstream wake as expected and dissipates near $x/D = 1.5$. The boundary layer is not consistent at the far edge of the measurement region near $x/D = 2$ as the window was in close proximity to the end of the test section within the wind tunnel. The second wake for $\theta = 15^\circ$ is similar in magnitude and longevity to $\theta = 0^\circ$. The boundary layer also follows the same path as $\theta = 0^\circ$, gaining elevation as it exits the test section. The effects of tilt continue to manifest as the high-speed flow remained trapped in the wind turbine array and increases in elevation more rapidly than was observed for $\theta = 0^\circ$. When $\theta = -15^\circ$, the velocity deficit is again the lowest in magnitude of the three angles. The flow above, however, does not exhibit the same altitude gain and hovers at $y/D = 0.5$ throughout the measurement region. These dynamics suggests the benefits of accessing high-speed flows with crashing wakes from negative tilt angles may provide residual benefit beyond the two immediately affected turbines.

Figure 5: *Normalized streamwise average velocities for $\theta = 15^\circ, 0^\circ, -15^\circ$ with turbines to scale. Immediately behind the 3rd row, tilt induced variations in wake magnitude and vertical displacement are visible which extend through subsequent rows.*

Contours of the average wall-normal velocity field $\bar{V}/U_\infty$ for $\theta = 15^\circ$, $\theta = 0^\circ$, and $\theta = -15^\circ$ provide additional insight on tilt dependent phenomena (Fig. 6). Like the streamwise velocity contours, the inflow into the 3rd row is statistically uniform across values of θ by design. Immediately behind the 3rd row, tilt angle specific effects are visible in the magnitude of the wall-normal velocity component. For the unaltered turbine at $\theta = 0^\circ$, low positive velocities are observed from $y/D = 0.25$ to the floor and relatively low negative velocities are found above $y/D = 0.25$. For $\theta = 15^\circ$, a large region of positive velocity is present directly behind the turbine and spans the interrogation area. Contrarily to wakes in the streamwise mean velocity fields, the area of positive velocity does not display vertical displacement and remains below $y/D = 0.25$. Despite not deflecting itself, the positive wall-normal wake is

likely responsible for the duration of shift in wake elevation noted in the streamwise velocity field. When the opposite angle of $\theta = -15^\circ$ is observed, the opposite behavior presents itself. A wake region of negative wall-normal velocity is generated behind the upper portion of the rotor between $y/d = 0$ and $y/D = 0.5$. This wake does not deflect vertically and is short lived, dissipating near $x/D = 1.5$. In the same manner as the positive wake for $\theta = 15^\circ$, this brief negative wake is likely the driving force behind the downward wake translation described in the streamwise velocity field.

Entering the 4th row, the wall-normal velocity field is unique for each value of θ . A trace wake of positive velocity is visible entering the measurement window at $y/D = -0.25$ for $\theta = 0^\circ$. Closer to the 4th row, the wake vanishes and immediately before the 4th row, the velocity field parallels the inflow to the 3rd row. For $\theta = 15^\circ$, the positive velocity wake noted upstream is the dominant feature. This wake begins to recover at $x/D = 1$ but persists well into the 4th row and is visible at the turbine edge of the measurement region. The velocity field mirrors the inflow into the 3rd row for $\theta = -15^\circ$. The measurement window is devoid of lingering features suggesting improved wall-normal wake recovery for negative tilt angles.

The magnitude of the velocity deficit behind rotors in the 4th row are lower in comparison to the wakes present behind the 3rd row and are all positive in sign. Wake longevity varies with tilt angle as the wake for $\theta = 15^\circ$ extends well beyond the region of measurement whereas for $\theta = -15^\circ$ the wake begins dissipating by $x/D = 1.5$. $\theta = 0^\circ$ is between the two extreme tilt angles which suggests a trend between increasing tilt angle and enhanced wall-normal wake longevity downstream.

Figure 6: *Normalized wall-normal velocities for $\theta = 15^\circ, 0^\circ, -15^\circ$ with turbines to scale. Immediately behind the 3rd row, the wall-normal velocity is observed to change direction obtaining a positive value for values of $\theta < 0$. Vertical noise was identified at $x/D = 1.5$ in front of the 4th row, however, this noise was not found to affect the mean statistics or subsequent analyses.*

Average Reynolds Shear Stress Field

Contours of the average in-plane Reynolds shear stress $\overline{u'v'}/U_\infty^2$ demonstrate a response to changes in tilt angle across $\theta = 15^\circ$, $\theta = 0^\circ$, and $\theta = -15^\circ$ (Fig. 7). As with the streamwise and wall-normal average velocities, the inflow into the 3rd row displays the same behavior for all values of θ . Moderate positive stresses from the upstream turbines are visible near $y/D = -0.25$ which dissipate by $x/D = 1$. A region of negative stresses exists near $y/D = 0.5$ spanning the measurement window.

Behind the 3rd row, a wake region of Reynolds stresses is generated behind the rotor. The sign is rotation dependent with large negative stresses behind the top

tip at $y/D = 0.5$ and lower positive stresses behind the bottom tip at $y/D = -0.5$. A small wedge of alternating stresses is visible immediately behind the nacelle at $y/D = 0$ which dissipates by $x/D = 1$. Tilting the turbine produces changes in the Reynolds stress magnitude as well as the vertical position of the stress regions. Behind the unmodified turbine with $\theta = 0^\circ$, the Reynolds stresses are symmetric about $y/D = 0$. The negative Reynolds stress region is moderately stronger than the complementary positive area. Positive stress are bounded between $y/D = -0.5$ and $y/D = 0$ and negative stresses are present from $y/D = 0$ to $y/D = 0.5$. Positive tilt strengthens the Reynolds stresses as shown by the increased magnitude of both positive and negative stresses for $\theta = 15^\circ$. Additionally, implementing a positive tilt angle has forced the Reynolds shear stress to create a stronger shear layer at the top tip which is propagated into the next row of turbines. This vertical shift has allowed the area of increased Reynolds stress to expand, occupying $y/D = -0.5$ to $y/D = 0.75$ and spanning the measurement region. Flipping to $\theta = -15^\circ$, the Reynolds stresses are far lower in magnitude, diminishing to half the magnitude of $\theta = 15^\circ$. The negative tilt angle imparts a shift of the stress regions down by $0.2D$ and the area occupied by heightened stresses has contracted rather than expanded.

In front of the 4th row, large variations in Reynolds stress are visible between values of θ . At a null tilt angle, $\theta = 0^\circ$, the Reynolds stresses have degenerated and resemble the inflow to the 3rd row. Weak negative stresses are found near $y/D = 0.5$ and a short-lived positive stress exists between $y/D = -0.5$ and $y/D = 0$. At $\theta = 15^\circ$, the Reynolds stresses are greater in magnitude and streamwise longevity than for $\theta = 0^\circ$. The flying wake described in the streamwise velocity field has formed a corresponding flying stress region of negative stresses extending from $y/D = 0.4$ beyond the range of measurement. Low positive stresses are present near $y/D = 0$ and display increased streamwise longevity over $\theta = 0^\circ$. Negative tilt angles display

greatly reduced Reynolds stresses. For $\theta = -15^\circ$, patches of weak negative stresses remain near $y/D = 0.5$. Positive stresses are entirely absent in the measurement region. Recalling the lack of wake features in the streamwise and wall-normal velocity fields, the absence of positive stresses supports crashing wakes improve wake recovery downstream. It is worth noting that negative tilt angles incur losses from mast-rotor interactions and therefore generate weaker wakes which may account for a portion of the improved wake recovery.

Behind the 4th row typical Reynolds stresses are established for all values of θ . Positive stresses are clustered between the rotor and bottom tip while negative stresses exist between the rotor and top tip. Their magnitudes are different thus leading to the conclusions that tilt angles modify the inflow conditions into subsequent rows of wind turbines.

Figure 7: *Normalized average streamwise Reynolds stresses for $\theta = 15^\circ, 0^\circ, -15^\circ$ with turbines to scale. The region of negative stresses in the bottom right corner immediately in front of the 4th row was identified as noise and subsequently neglected from discussion and further analysis.*

Streamwise Averaged Vertical Profiles

Streamwise averaged profiles covering the full range of θ allow further insight into wake behavior in response to tilt angles (Fig. 8). Streamwise variance was calculated for each parameter to ensure the averaged profile accurately represented wake phenomena within the measurement window. In addition, error from vector removal during data processing was calculated for each averaged profile. Both streamwise variance and processing error were found to be at least two orders of magnitude lower than the range of each parameter. The average streamwise velocity (Fig. 8a) entering the 3rd row has largely regained the free stream velocity and resembles the boundary layer. Upon exiting the 3rd row, differences in wake velocity and elevation due to tilt

are immediately apparent. Positive tilt angles shift the wake up into the boundary layer as noted previously. Increasing θ from $\theta = 0^\circ$ to $\theta = 15^\circ$ produces successive increases in wake translation and velocity deficit. When $\theta = 5^\circ$, the wake center velocity is approximately half of the free stream velocity and by $\theta = 15^\circ$, the wake center velocity is down to 0.4 the free stream velocity. This trend continues for negative values of θ where further negative tilts result in consecutively weaker wakes with greater displacements. For $\theta = -5^\circ$ the wake center velocity is also 0.5 the free stream velocity which is approaching 0.6 the free stream velocity at $\theta = -15^\circ$. This suggests the results discussed in prior sections apply to small tilt angles where negative tilt produces weaker velocity deficits. By the 4th row, the streamwise velocity has recovered and resembles the inflow to the 3rd row. However, small differences are evident further from the turbine as y/D approaches $y/D = 0.5$ and $y/D = -0.5$. Positive tilts have generated a flying wake and as such possess lower mean velocities along y/D . The measured reduction in streamwise velocity shows positive angles increase wake longevity and interrupt entrainment from the flow above the wind turbine array. Negative tilt angles possess correspondingly higher mean velocities indicating even small angles can vertically draw additional flow from the outer flow into the turbine array thereby encouraging entrainment. Beyond the 4th row, differences in streamwise velocity below the turbine are no longer evident. For $y/D > 0$, positive tilt angles continue to maintain lower mean velocities than negative tilt angles.

Wall-normal average velocity profiles (Fig. 8b) in front of the 3rd row are uniform for all tilt angles and do not show the effects of upstream turbines as expected. Behind the 3rd row, significant variations in both the magnitude and sign of the wall-normal velocity are present as discussed previously. Positive values of θ create a region of positive wall-normal flow below $y/D = 0$ with a peak of -0.1 the free stream

velocity. Negative values of θ produces the opposite effect with an area of negative wall-normal velocity above $y/D = 0$ at 0.05 the free stream velocity. Smaller tilt angles reproduce the same effect at lesser magnitudes although even the lowest values of $\theta = \pm 5^\circ$ introduce wall-normal flow at 0.05 and -0.025 the free stream velocity, respectively. Wall-normal motion persists downstream and is still present for all values of θ approaching the 4th row. The mean wall-normal velocities are closest to zero for negative tilt angles indicating faster downstream wake recovery. For positive tilt angles, the magnitude of the wall-normal velocity remains unchanged at 0.1 the free stream velocity. This finding is complementary to the enhanced streamwise wake longevity noted previously implying positive tilt angles also produce strong wall-normal wakes. Behind the 4th row, there is negligible variation in average wall-normal velocity between values of θ below $y/D = 0$. The profiles are completely converged indicating observed motion beyond the 4th row to be the result of turbine rotation and mixing. Above $y/D = 0$ the wall-normal motion is dominated by turbine rotation although positive tilt angles maintain higher positive velocities. As was observed for streamwise average velocity, the effects of positive tilt angles are observed to affect wall-normal motion through subsequent turbines.

Streamwise averages of the Reynolds shear stresses (Fig. 8c) are uniform for all values of θ . Lingering negative stresses occupy the region above $y/D = 0$ with complementary positive stresses below $y/D = 0$ from prior turbine rows. Tilt angle in the 3rd row produced changes in the vertical displacement and magnitude of the Reynolds stresses for different values of θ . As noted previously, positive values of θ shift the Reynolds stresses up into the boundary layer near $y/D = 0.5$ while negative values of θ push the stress regions towards the ground. Additionally, positive tilt angles result in higher Reynolds stresses with $\theta = 15^\circ$ doubling the magnitude of the stresses for $\theta = -15^\circ$. As expected, smaller tilt angles generate lower vertical

deflection of the stress regions as well as weaker Reynolds stresses overall. Entering the 4th row, Reynolds stresses from positive tilt angles are present and offset upwards by $0.2D$. Negative tilt angles result in marginal positive negative between $y/D = 0$ and $y/D = 0.5$ but have largely dissipated. Behind the 4th row, differences in the Reynolds stresses remain above $y/D = 0$ for positive tilt angles but are absent below the turbine where a single positive peak dominates.

Vertical transport of mean turbulence kinetic energy behaves in similar manner to the Reynolds stresses (Fig. 8d). In front of the 3rd row, kinetic energy flux mirrors the Reynolds stresses in the same region. Behind the 3rd row, varying tilt angle results in differing transport dynamics. Positive tilt angles encourage transport of kinetic energy upwards into the boundary layer. Peak vertical energy flux occurs at $y/D = 0.5$ for $\theta = 15^\circ$ with a complementary peak at $y/D = 0.25$ for $\theta = -15^\circ$. A broader region of positive energy transport is present from $y/D = 0.25$ to $y/D = -0.5$. Here $\theta = 15^\circ$ generates the largest energy flux near $y/D = -0.2$ followed by $\theta = 10^\circ$ and $\theta = 5^\circ$. Negative tilt angles have the same general response as positive tilt angles. The magnitude of the kinetic energy transport is comparable between positive and negative tilt angles and does not vary significantly between values of θ . Peaks are centered at $y/D = 0.25$ for negative fluxes and $y/D = -0.5$ for positive fluxes indicating tilt angle affects the elevation of peak kinetic energy transport. Varying the altitude of peak vertical energy flux has considerable influence on the amount of energy available to subsequent turbines. Because kinetic energy transport flows along y , kinetic energy transport is spaced across the distance over which energy flux occurs. Therefore negative tilt angles provide more kinetic energy to subsequent turbines by directing a similar amount of kinetic energy transport as positive tilt angles into a smaller area. Coupled with improved wake recovery and entrainment, negative tilt angles result in additional usable kinetic energy. Further downstream,

positive tilt angles continue to advance vertical energy flux into the boundary layer. Negative fluxes are present for positive tilt angles from $y/D = 0.25$ extending up beyond the measurement window. Negative tilt angles form marginal negative fluxes near $y/D = 0.25$. Beyond the 4th row, vertical energy flux imitate the Reynolds stresses in this area with complementary peaks of positive and negative transport at $y/D = -0.25$ and $y/D = 0.25$, respectively. Behind the nacelle and top tip, positive tilt angles create negligible differences in the vertical transport of mean kinetic energy.

Figure 8: Streamwise average profiles for: **(a)** average streamwise velocity normalized by the free stream velocity **(b)** average wall-normal velocity normalized by the free stream velocity **(c)** Reynolds stresses normalized by the square of the free stream velocity **(d)** vertical transport of mean turbulence kinetic energy.

Conditional Sampling

From the average Reynolds stresses, characterization of sweep and ejection events as a result of tilt modification was performed via conditional sampling (Fig. 1). The relevant quadrants from conditional sampling, Q_2 and Q_4 , highlight the direction and magnitude of vertical momentum flux within the turbine wake (Fig. 9a). Ejections relate to upward momentum transfer and in the case of a horizontal axis turbine are expected from the turbine extending into the boundary layer. Sweeps denote downward momentum transfer and for horizontal axis turbines typically exist in the same region as ejection events as both are predominant in high shear areas. Both sweeps and ejections were observed for $\theta = 0$ from $y/D = 0$ beyond the region of measurement.

Because both sweep and ejection events exist in the same physical region, stream-wise averages of ΔS_0 were used to quantify the relative importance of sweep to ejection events resulting from turbine tilt (Fig. 9b). The inflow into the 3rd row has moderate ejection-dominated regions below the turbine at $y/D = -0.5$ and from $y/D = 0.5$ beyond the region of measurement from upstream turbines for all values of θ . Behind the 3rd row, sweep events are present at different elevations for each value of θ with positive tilt angles shifting the sweep-dominant region up and negative tilt angles creating a downward shift. The magnitude of sweep preference is 0.25 for all values of θ . Larger values of θ produce greater displacement magnitudes; $\theta = 15^\circ$ pushed the sweep-dominant region towards $y/D = 0.2$ while $\theta = -15^\circ$ resulted in a peak near $y/D = -0.2$. Positive tilt angles also produced an ejection-dominated region below the turbine centered at $y/D = -0.2$. This feature is not present for negative tilt angles and indicates positive tilt draws momentum from below the turbine as it projects up into the boundary layer. In front of the 4th row, the ejection dominant region is

still present for positive tilt angles although the magnitude has decreased to marginal values. Negative tilt angles gained an ejection preference above $y/D = 0.25$ indicating these angles are successfully drawing momentum from the boundary layer. The sweep-dominant peaks observed behind the 3rd row are no longer visible entering the 4th row due to downstream wake recovery. Behind the 4th row, all values of θ demonstrate a sweep-dominant region centered around $y/D = 0.2$ and an ejection-dominant region at $y/D = -0.5$.

(a) Normalized sweep and ejection components for $\theta = 0^\circ$ with turbines to scale. Ejections, q_2 , are presented on the top row with sweeps, q_4 , on the bottom row.

(b) Streamwise average profiles of ΔS_0 .

Wake Center Tracking

Figure 10: Procedure for implementing the Gaussian wake center tracking algorithm for an arbitrary value of x in $\theta = 15^\circ$. On the left, the normalized average streamwise velocity field is depicted with a dashed line indicating the location of the vertical velocity profile. The velocity profile minus the mean shear gradient and its Gaussian fit are shown to the right.

Wake centers were computed by fitting a Gaussian profile to the streamwise velocity deficit following the approach outlined in [13]. The average streamwise velocity field for each value of θ was separated into vertical profiles along x . The mean shear gradient was then subtracted from each profile to isolate the wake velocity deficit by removing boundary layer effects. From here, a Gaussian curve was fit to each profile by minimizing the nonlinear least-squares function such that the center of the Gaussian provided a reasonable estimate of wake center (Fig 10). In the very near wake behind the 3rd and 4th rows, the velocity deficit took the form of a bimodal Gaussian which merged into a single Gaussian with distance downstream consistent with [13]. Wake centers were observed to deflect vertically with tilt and remain offset entering the 4th row (Fig. 11). Small non-zero wake displacement was present for $\theta = 0^\circ$, particularly far downstream. Additionally, wake center meandering was recorded leading

into the 3rd and 4th rows although some of the observed meandering may stem from error fitting a Gaussian profile to the velocity deficit far downstream. Larger values of θ produced correspondingly greater wake translation and increased the downstream distance to reaching maximum displacement (Fig. 12). All values of θ resulted in vertical wake displacement with the lowest maximum translation recorded for $\theta = -5^\circ$ of $0.05D$. Negative tilt angles reached peak displacement between $x/D = 1.5$ and $x/D = 2$ behind the 3rd row before returning towards $y/D = 0$ as the wake recovered. Positive tilt angles required greatly increased distance downstream to reach peak displacement with $\theta = 15^\circ$ requiring nearly $6D$ to peak just before entering the 4th row. Positive tilt angles persisted through subsequent turbines to create a vertical shift in wake center beyond the 4th row. $\theta = 15^\circ$ deflected the wake center up by $0.1D$ while $\theta = 10^\circ$ and $\theta = 5^\circ$ were skewed upwards by $0.05D$ at the end of the measurement windows. Negative tilt angles remained at or marginally below $y/D = 0$ downstream of the 4th row.

Figure 11: Wake centers shown over the normalized streamwise velocity fields for $\theta = 15^\circ, 0^\circ, -15^\circ$ with turbines to scale.

Changes in the vertical transport of mean turbulence kinetic energy between the top tip and bottom tip were computed along the wake centerline and averaged in the streamwise direction. This was performed to generate a single metric for quantifying the effect of turbine tilt between tilted and horizontal turbines (Table 1). Behind the 4th row the different values of θ do not substantially alter wake behavior between the top and bottom tip. From the 3rd row extending into the 4th row a sequential increase was observed where decreasing tilt from $\theta = 15^\circ$ to $\theta = -15^\circ$ produced smaller differences in wake behavior from top tip to bottom tip. Positive tilt angles result in larger deviations between top and bottom tip while negative tilt angles result in weaker wakes with less change between top and bottom tip.

Figure 12: Wake centers for all values of θ with turbines to scale. Vertical wake meandering was noted in the inflow to both the 3rd and 4th rows.

θ	R_{3-}, R_{4+}	R_{4-}
15°	0.20	0.24
0°	0.14	0.26
-15°	0.08	0.21

Table 1: Average streamwise difference in $\langle \overline{u'v'U} \rangle_x$ from top to bottom rotor tip for $\theta = 15^\circ, 0^\circ$, and -15° adjusted for vertical wake displacement.

Model Evaluation

Comparisons of the maximum observed wake center displacement to numerical and analytic models (Table 2) demonstrate a high level of agreement with numerical results. Maximum wake center deflection for both positive and negative tilt angles were simulated within $0.01D$. Net efficiency shows a moderate agreement between simulation and experiment for $\theta = 15^\circ$ where low net losses of -0.5% and -2.7% are observed, respectively. Despite tilting up into the outer flow, positive tilt angles reduce the overall operating efficiency for the affected turbines. This effect aligns with previous results indicating positive θ projects a strong wake into the boundary layer inhibiting entrainment. For $\theta = -15^\circ$, net power findings for simulation and experiment diverge considerably. A small gain in net performance of 3.8% was noted in simulation from successfully drawing high-speed flow into subsequent rows. However, for the present configuration, performance losses experienced in the 3rd row did not outweigh increases in the 4th and a loss of -8.2% is reported. The large

discrepancy between simulation and experiment is believed to be due to the effects of mast-rotor interactions. Close proximity between the rotor and mast is known to generate regions of high instantaneous pressure which reduce turbine performance [18]. These interactions were present in experiment for negative tilt angles but are not implemented in the actuator line model employed in simulation [13, 14].

Analytic models were evaluated by substituting the model turbine thrust coefficient and tilt angle to generate an estimate of wake deflection behind the 3rd row. A wake expansion parameter of 0.1 was used in Equation 8 as prescribed in [19] to facilitate accurate comparisons. In both cases, analytic models overestimate maximum vertical wake translation by a significant margin. Both models assume wake symmetric deflection leading to a greater margin of overestimation for negative tilt angles. The models also assume increasing wake translation with distance downstream which is not representative of the observed behavior where wakes reach a peak before returning to $y/D = 0$. Because negative tilt angles rapidly reach their maximum displacement then return, the difference in estimating the streamwise peak location for negative angles is much greater than for positive angles. Equation 8 yields the largest variation in predicting maximum wake offset with overestimates of $0.09D$ and $0.13D$ for $\theta = 15^\circ$ and $\theta = -15^\circ$, respectively. The magnitude of difference between estimates with Equation 8 and experimental result indicate yawed wake models are not well suited for immediate application predicting tilt phenomena. Furthermore, the discrepancy in predicting wake deflection indicates two of the assumptions in the original formulation of Equation 8 may not hold true for tilted turbines. Specifically, the assumption of a uniform velocity field outside the wake region and negligible pressure effects may need to be revised due to the influence of the boundary layer. The model presented in Equation 9 provided slightly improved predictions of maximum wake offset with respective overestimates of $0.04D$ and $0.08D$ for $\theta = 15^\circ$ and

$\theta = -15^\circ$. However, the model assumes linear wake offset which does not reflect measured behavior, especially for negative tilt angles.

θ	Wake Offset (y/D) [13]	Wake Offset (y/D) [19]	Wake Offset (y/D) [15]	Wake Offset (y/D)	% Δ P [14]	% Δ P
15°	0.18	0.28	0.23	0.19	-0.5	-2.7
0°	0.03	0	0	0.09	0	0
-15°	-0.14	-0.28	-0.23	-0.15	3.8	-8.2

Table 2: Comparison of measured wake characteristics, in bold, with simulated [13, 14], and analytic [19, 15] results for $\theta = 15^\circ$, 0° , and -15° . Net combined power production for the 3rd and 4th rows are reported as percent change relative to $\theta = 0^\circ$.

5 Conclusions

Tilt deflection was evaluated as a method to improve efficiency for both terrestrial and offshore wind plants in a wind tunnel experiment. The instantaneous velocity field and power measurements were recorded in a Cartesian array of model wind turbines. For full consideration on the effects of tilt angle on wake behavior and wind plant performance both positive and negative tilt angles were considered.

Analysis of the streamwise average velocity revealed negative tilt angles to produce lower magnitude wakes with improved recovery and for these wakes to evolve into crashing wakes downstream. This effect was observed to draw high-speed flow from the boundary layer into the plant improving entrainment. The wall-normal average velocity displayed large variations in magnitude between positive and negative tilt angles behind the tilted turbine row. Positive tilt angles generated large positive wall-normal velocities with substantial longevity while negative tilt angles created moderate negative wall-normal velocities. The positive velocity region from positive tilt angles persisted through the 4th row and enhanced the magnitude, elevation, and streamwise longevity of subsequent wakes.

Reynolds stresses increased in magnitude and vertical position with increasing tilt angle, reaching a peak difference of twice the magnitude for $\theta = 15^\circ$ compared to $\theta = -15^\circ$. Positive tilt angles also generated larger regions of positive stresses behind the turbine which persisted into the 4th row. Beyond the 4th row, positive tilt angles maintained higher Reynolds stresses. However, below the turbine there were no measurable differences for differing values of θ .

Vertical transport displayed similar behavior to the Reynolds stresses with positive tilt angles having greater vertical transport at higher elevations. Negative tilt angles produced a comparable amount of vertical energy flux in a smaller area greatly

improving kinetic energy availability downstream. Differences in vertical transport between values of θ lasted through the 4th row above the turbine affecting subsequent wake behavior.

Conditional sampling was used to quantify the importance of sweep vs. ejection events and thus downwards vs. upwards momentum transfer. A large sweep dominant region was observed behind the turbine which translated vertically with tilt angle. Positive tilt angles also showed an ejection dominant region below the turbine which was not present for negative tilt angles. In front of the 4th row, negative tilt angles generated a sweep dominant region above the turbine confirming they successfully introduced momentum from the boundary layer into the plant in this region.

Wake centers were tracked by fitting a Gaussian profile to the velocity deficit minus the mean shear gradient. Wake centers showed vertical translations of up to $0.2D$ for both positive and negative tilt angles. Negatively deflected wakes achieve maximum offset earlier downstream and return towards the turbine center while positively deflected wakes reach their maximum displacement far later downstream within $1.5D$ of the 4th row. Behind the 4th row, positive θ was found to result in successive wakes curving up into the boundary layer prolonging the wake enhancing effects of positive tilt. Differences in the vertical kinetic energy flux support these claims and show a linear trend in the magnitude of vertical flux with increasing tilt angle behind the 3rd row and into the 4th row. Comparison of maximum wake displacement to numerical and analytic models show good agreement only for simulated tilt behavior and not for analytic models. Two different models with linear and nonlinear features were compared to experimental data; both were found to overestimate maximum wake deflection. Changes in net power were compared to simulation and show agreement between simulated performance and experimental power measurements for positive tilt angles. Net power diverged between simulation and experiment for negative angles

likely due to mast-rotor interactions.

The experimental dynamics of tilted turbines have been recorded for the first time revealing previously unidentified phenomena. The far downstream influence of positive tilt and disruption of entrainment from the boundary layer are of particular importance to the design and operation of wind plants. Additionally, the experimental results indicate prior numerical work can successfully model wake deflection and plant production. While wake deflection alone did not produce significant changes in net plant efficiency, negative angles were observed to produce weaker, shorter-lived wakes and successfully draw high-speed flow into successive turbine rows. In practice, negative tilt angles would create unacceptably high risk of tower strikes, thus downwind turbine designs may be the preferred candidates for future work implementing tilt control.

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