Coriolis Forces on Wind Turbine Wakes within a Wind Farm

Natalie Violetta Frank
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Coriolis Forces on Wind Turbine Wakes within a Wind Farm

by

Natalie Violetta Frank

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

Master of Science
in
Mechanical Engineering

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Abstract

As wind plant footprints and turbine scales grow larger, understanding the interactions between mesoscale physical phenomena, such as Earth’s rotation, and large-scale farm wakes become increasingly important. Current field research notes spatial and temporal influences on the global farm wakes caused by Coriolis forces. However, using field experiments to study this is notoriously difficult as there is additional influence from wind veer in the atmospheric boundary layer caused by many factors ranging from terrain to the diurnal cycles. Experiments are performed on a wind plant under the influence of Coriolis forces. This is achieved by placing the wind plant on a rotating platform. The latter is 13m in diameter and can be filled with water up to 1-meter height. We find that, while the wake of an isolated wind turbine is not affected by inertial forces, they become relevant for the large scale wake from a wind plant. We therefore present experimental evidence on the role of Coriolis forces on the wake dynamics of a wind farm.
Acknowledgements

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Nomenclature

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<td>Atmospheric Boundary Layer</td>
</tr>
<tr>
<td>$Ro$</td>
<td>Rossby Number</td>
</tr>
<tr>
<td>$Fr$</td>
<td>Froude Number</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynholds Number</td>
</tr>
<tr>
<td>$C_{c,i}$</td>
<td>Coriolis force term</td>
</tr>
<tr>
<td>$f$</td>
<td>Coriolis frequency</td>
</tr>
<tr>
<td>$\epsilon_{ijk}$</td>
<td>Levi-Civita</td>
</tr>
<tr>
<td>$u_j$</td>
<td>velocity vector</td>
</tr>
<tr>
<td>$G_j$</td>
<td>Geostrophic wind vector</td>
</tr>
<tr>
<td>UGA</td>
<td>Université Grenoble Alpes</td>
</tr>
<tr>
<td>LEGI</td>
<td>Laboratoire des Écoulements Géophysiques et Industriels</td>
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<td>PIV</td>
<td>Particle image velocimetry</td>
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1 Introduction and Motivation

Renewable energy has gained popularity over the past couple decades. The burning of fossil fuels has lead to an increase in the CO$_2$ emissions which has contributed to climate change \[2\]. The negative impact fossil fuels have had on the health of our climate caused scientists and leaders to search for renewable forms of energy production. This need to find a solution has driven the wind energy sector to new heights.

Key discoveries in wind turbine development have lead to the technological advancement in this energy sector; maximum power of a wind turbine is proportional to the wind speed cubed, and blade tip speed of the turbine is proportional to wind speed. These two statements suggest that size of a turbine matters. With this discovery, wind turbines were designed to harness more energy by increasing in size. As the years go by turbines have grown physically larger [13]. Wind plant footprints have extended further and grown in numbers around the world. Additionally, there was massive growth in the rotor diameters [12]. With wind plants growing to larger scales than they have before, investigating the mesoscale impacts and interactions of these plants becomes increasingly important.

Evidence of far field wind plant wakes was published by Platis et al. [17]. This
study revealed that wind plants are causing wakes that persist up to 45 kilom downstream of the wind plant [17] and can be considered a mesoscale flow. This study showed the relevance of investigating the mesoscale interactions of these wind plant systems in the atmospheric boundary layer (ABL). The ABL is characterized by density stratification of air and Coriolis forces [15]. Due to this, the studying the influence of Coriolis forces on wind plant dynamics will aid in understanding of mesoscale flows from a wind plant.

As Earth rotates, Coriolis forces act perpendicular to the direction of motion of a moving body, deflecting the trajectory right in the northern hemisphere and left in the southern hemisphere [16], this is defined as the Coriolis effect. This is applicable to moving bodies, as well as large scale atmospheric circulations [16]. Coriolis forces vary depending on the position on earth. It increases with latitude, making the effect felt strongest at the poles of Earth [16]. Large offshore wind plants have been installed in the North Sea [9], and due to the proximity to the north pole, it is a region of high Coriolis forces. Preliminary wind resource assessment projects, such as the Global Wind Atlas, have developed wind power density and mean wind speed maps; both of these provide insight into the available wind resource and show that there are regions of high potential near the poles of the globe [3]. Coriolis forces might influence current wind plants further in the north and future wind plant installations that consider going to high power density spots towards the poles. In a region where there is a high density of wind resource, wind plants, and strong effects due to Coriolis, the motivation to understand this phenomena in the context of a wind plant dynamics becomes realized.

Coriolis forces have been an atmospheric effect often neglected by most wind
plant models. Extensive numerical studies discovered important insights when con-
sidering the Coriolis term, and suggest that it should not be neglected when consid-
ering plant-to-plant interactions, global plant wakes, power production and various
wake behaviors [19] [8] [11] [18] [1]. One aspect of wake behavior influenced by Cori-
olis still remains debated; the direction of wake deflection that results. Numerical
studies have investigated this and has lead some to the conclusion that wakes from
wind turbines will deflect clockwise [10] [20] [8], and others to conclude that wakes
will deflect anticlockwise [14] [7] [11] Despite the varying conclusions, the current
literature agrees that the Coriolis parameter in the context of a wind plant is not
trivial and should be studied in greater detail. With a trove of numerical research
the need for scaled experiments on this topic becomes greater. Experiments will
help to provide insight on wake behavior changes due to Coriolis.

There are two crucial considerations for ABL recreation; inertial Coriolis forces
from the rotation of the Earth and the stratification of flow. Both can be represented
with the non-dimensional numbers Rossby, $Ro$ a ratio of inertial to centrifugal forces,
and Froude, $Fr$ a ratio of inertial to gravitational forces. Generally, wind plant flow
is characterized by high Reynolds numbers, $Re$. Studying wind plants in mesoscale
ABL conditions requires the manipulation of the $Ro$ number. Natural systems
have large $Re$ numbers, and very small $Ro$ numbers. Achieving these scales in a
laboratory setting is difficult, high $Re$ can be achieved through larger velocities and
length scales. Smaller $Ro$ numbers can be achieved through higher rotational speeds.

These experiments are performed using the rotating Coriolis platform. A pow-
erful facility equipped to overcome the challenges of observing mesoscale flows on
a laboratory scale of one meter. The platform is 13m in diameter, and has a max-
imum rotational speed up to 2 rotations per minute. The large dimensions and high rotational speed of the platform keeps $Ro$ numbers similar to natural flows while inducing Coriolis forces and maintaining stratification, reproducing turbulent boundary layers comparable to the oceanic or atmospheric model. The experiments presented here are the first of its kind, introducing new possibilities for future research into the fundamental mesoscale observations within and following a wind plant.
Theory

The impact of Coriolis forces on a wind turbine wake in a wind plant was investigated. The Navier-Stokes momentum equation for this research was defined as follows:

$$u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} - \frac{\partial u'_i u'_j}{\partial x_j} + f_x + f_c \epsilon_{ijk} \hat{e}_k (u_j - G_j)$$  \hspace{1cm} (2.1)

The Coriolis term is defined as $C_{c,i} = f_c \epsilon_{ijk} \hat{e}_k (u_j - G_j)$, where $f_c = 2\Omega$ is the Coriolis frequency of the rotating Coriolis platform, $\epsilon_{ijk}$ is the Levi-Civita, $\hat{e}_k$ is the unit vector, $G_j$ is the geostrophic wind vector, and $u_j$ is the velocity vector. This definition is consistent with van der Laan et al [19]. Both geostrophic wind and Coriolis frequency were constant for the experiments. The concept of the Coriolis effect can be understood by a balance between the pressure and the Coriolis forces with some competition by the Reynolds stresses. The $x$ and $y$ components of the Coriolis force term can be written respectively as

$$C_{c,1} = f_c (v - G_y) \quad C_{c,2} = -f_c (u - G_z).$$  \hspace{1cm} (2.2)

To simplify, the wake deflection can be assumed to be caused by the $y$ component of the Coriolis force, $C_{c,2}$. $C_{c,2}$ in the northern hemisphere acts perpendicular and to the
right of an air mass. In the case of equilibrium where pressure, Coriolis and Reynolds stresses are balanced with each other, the air mass is in geostrophic balance and will not be deflected. When the air mass forces are out of balance, this causes deflection. In order for the forces to be out of balance, equation 2.2 shows that only a change in the velocity component is what causes a change in the Coriolis force strength. If the streamwise velocity, decreases then the $y$ component of the Coriolis force will increase. This causes an imbalance between forces, and the Coriolis force dominates. This means the deflection direction of the air mass will follow the direction of the Coriolis force. In the context of the experiments, simulating the northern hemisphere rotation, this decrease in velocity causes a clockwise deflection. If the streamwise velocity increases, the Coriolis force will decrease and the dominating force in the imbalance is the pressure force, which acts in the opposite direction of the Coriolis force. This implies the deflection direction will follow the direction of the pressure force, in the context of the experiments, an increase in velocity will cause an anti-clockwise deflection. The Reynolds stress is also an influencing parameter, and was investigated in these experiments.
3 Experimental Setup

The Coriolis rotating platform at Université Grenoble Alpes (UGA), Laboratoire des Écoulements Géophysiques et Industriels (LEGI) is a circular platform with a tank 13m in diameter, rotating at a maximum speed of $2 \text{rot/min}$. The Coriolis platform is currently the largest rotating platform that allows for experimental investigation of atmospheric and oceanic geophysical flows [6]. The large size minimizes the influence of viscosity and centrifugal forces, recreating the turbulence seen in the atmospheric flows and the high rotational speed induces Coriolis forces on the experiments [6]. Flow is generated by rotating the platform at a specified speed that corresponds to a Coriolis frequency, and a free stream velocity value [5]. Once the flow is in solid body rotation, the effects of Coriolis forces on the experiments can be studied independently [5]. An image of the Coriolis rotating platform is seen in figure 3.1.

The experiments were performed with water in order to generate Coriolis forces in the flow. The platform is filled to a depth of 1m. The results discussed in this paper are performed with the platform rotating at $2 \text{rot/min}$ which corresponds to a Coriolis frequency of $0.41 \text{s}^{-1}$ and a free-stream velocity of $50 \text{cm/s}^{-1}$.

The Rossby number ($Ro$) includes this Coriolis frequency term. $Ro$ is a dimensionless number of the ratio of inertial forces to the Coriolis force and defined as
$Ro = \frac{U}{L}$, where $U$ and $L$ are its characteristic velocity and length scale respectively. $Ro$ number is important in geophysical flows in the ocean and the atmosphere. This is a key parameter for these experiments, it will create the connection between experimental results and field scales. Large $Ro$ means inertia forces dominate. Small $Ro$ means the Coriolis force dominates. $Ro$ for the experiments performed was $Ro = 8.13$ when a characteristic velocity is chosen to be the measured free-stream incoming velocity, $50\text{cm s}^{-1}$, and the characteristic length is the turbine rotor diameter, $15\text{cm}$, and a Coriolis frequency chosen for all of the experiments, $0.41\text{s}^{-1}$. This number is in line with the purpose of the equipment used. The flow in the laboratory setting is Coriolis force dominated and not inertial force dominated, therefore small $Ro$ number.

This work focuses on various experimental configurations. Across all configu-

**Figure 3.1:** Image of the Coriolis platform from video footage by Zeste de Science / Les sèries originales du CNRS [4].
rations, camera filter views, laser setup, Coriolis frequency, and incoming velocity were kept the same. Free stream flow of the Coriolis platform was measured. It consisted of no wind turbines and a measured incoming flow velocity of 50 cm/s. Number of turbines was the changing variable. Table 3.1 lists the experimental cases discussed.

<table>
<thead>
<tr>
<th>Case</th>
<th>Turbines</th>
<th>Configuration</th>
<th>Streamwise</th>
<th>Spanwise</th>
<th>Turbine direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Single</td>
<td>None</td>
<td>None</td>
<td>WRT flow</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>Grid</td>
<td>3D</td>
<td>3D</td>
<td>WRT flow</td>
</tr>
</tbody>
</table>

**Table 3.1:** Table of experimental configurations. WRT flow was the turbine orientation. WRT signifies that each turbine in the plant was rotated to face the respective incoming rotational flow.

Turbines of the farm are aligned to the respective free stream rotational flow. The schematic of the experiment is shown in figure 3.2. The center of the farm was aligned parallel with the radius of the tank, was placed 471.0cm away from the center. The edge of the farm at this position is 104cm from the edge of the tank, sufficient distance to avoid wall interactions.

Particle image velocimetry (PIV) was used to visualize the flow of the experiments. All experimental cases utilized one camera and two lasers. The camera had a filter view of a 4m × 3.5m. Two lasers on opposite sides of one another reduced the cast shadows on the platform from the wind turbines. Each laser was a 532nm wavelength laser, at 25W and 10W of power for laser 1 and 2 respectively. Both lasers were placed at the hub height of the wind plant, \( h = 13.5\text{cm} \). The particles used in the experiments were neutrally buoyant with a particle size of 60µm. PIV image processing was done with Matlab programs created by Joel Sommeria at LEGI.
Figure 3.2: Top view of the experimental set up on the Coriolis platform. The figure on the left shows the measurements of the farm placement relative to the tank. The schematic on the right shows the equipment set up on the platform. The PIV laser sheets were placed at hub height of the farm, \( h = 13.5 \text{cm} \). Images for PIV measurements were taken from above, images are top views of the farm.

Based on the size of the rotating platform, a turbine rotor diameter of 15\( cm \) and a hub height of 13.5\( cm \) were chosen. These turbine dimensions needed to be large enough to resolve information, while also being small enough to not interfere with recirculating flow, dynamics at the surface of the water, or wall effects. The rotor diameter (\( D \)) to hub height, (\( h \)) ratio of the scaled wind turbine is 1.11, The scaling ratio wind turbine is 1 : 780. Due to the limitations of the experiments performed underwater, turbines were constructed mechanically, and resistive loads were simulated by a tightened screw placed at the hub of the turbines.

Operating on a rotating frame that does not take into account latitude, the Coriolis parameter becomes \( f = 2\Omega \). The same rotation speed is used for each experimental case, \( 2\text{rot/min} = 0.209 \text{rad/s} \), so the Coriolis parameter is \( f = 0.41 \text{s}^{-1} \).
Based on previous studies, $D$ will be used for the characteristic length, and incoming flow speed is used as the characteristic velocity, $U$.

$Ro$ is used to scale the experimental set up to atmospheric conditions. The size of the rotor diameter in the experiments is 15cm. $Ro$, based on rotor diameter and incoming velocity, can be used to find the real life dimensions that equates. Assuming an atmospheric wind speed of $5\text{ms}^{-1}$ and a mid-latitude Coriolis parameter, $f = 10^{-4}$, $Ro$ of the experiments and the atmospheric conditions can be compared to find the proper field length scale.

\[
\frac{5\text{ms}^{-1}}{L(10^{-4})} = \frac{0.5\text{ms}^{-1}}{0.15\text{m}(0.4\text{s}^{-1})}
\]

\[L = 600\text{m}\]

This tells us that the rotor length used in the experiments corresponds to a 600m diameter rotor in a life size wind plant. This value when used for total farm length, is a realistic size.

Reynolds number calculation of the experiments based on in flow speed, and rotor diameter length scale. Reynolds number for these experiments are $Re = 75,000$. This Reynolds number is sufficient enough for wind turbine experiments.
When a wind plant is subjected to Coriolis forces, the wakes deflect from the turbine [11] [19]. The following images are PIV measurements taken from several experiments. Images are taken at $h$ in Cartesian coordinates. Polar coordinate figures are shown in this paper to better visualize the deflections of these wakes. Figure 4.1 refers to the dimensions of the experimental set up.

**Figure 4.1:** Schematic on the left is a top view schematic of the rotating Coriolis platform. The schematic on the right is a zoomed in view of the wind plant placed on the platform. The plant rows are labelled I, II, III. The plant columns are labeled by $a, b, c, d$.

Literature has cited that the influence on a single turbine is negligible, and
Coriolis forces are more influential in wind plant flow. To investigate this claim, a single turbine experimental case was performed. From figure 4.2 the wake does not deflect from its radial position. This is seen by the wake of the turbine heading straight back. Indicating the effect of Coriolis on a single wind turbine is negligible, a result other numerical studies have observed [19].

Figure 4.3 is the mean streamwise velocity of the 12 turbine $3D \times 3D$ wind plant experiment in Cartesian coordinates. In figure 4.3, there is visibly strong wake deflections following each turbine, and then an almost fully merged wind plant wake
about $20D$ from the plant entrance in the anticlockwise direction. Additionally, the wakes of each turbine impinge upon one another through out entire rows. From figure 4.3 two regions of deflection can be observed. Wake deflection direction is not consistent within the plant, there is a dependence on downstream position, $x$. Within the first column, $a$, the deflection appears to go right, or in the clockwise direction. Around column $c$, $6D$, is when the wakes turn back to the anti-clockwise direction.

Using $Ro$ to give the deflection results context helps to understand why literature has seen clockwise and anti-clockwise rotations. The $Ro$ calculations in the previous section confirmed that the view of the experiments, $4m$ in length, corresponds to a view of $16km$ on a real wind plant. This is realistic for far field wind plant wakes. The $Ro$ scaling can be used to contextualize what is happening within the first column of turbines. Figure 4.3 in column $a$ shows all turbines wakes with a clockwise direction of rotation. The $Ro$ scaling based on rotor diameter within the first column $a$, corresponds to $3000m$ on a real wind plant. This length is similar to results gathered by van der Laan and Sørensen of wake deflection within the first wind plant length [20]. In these distances behind a wind plant entrance, wake deflection appears to rotate clockwise. However, looking further downstream the wakes deflect anti-clockwise, in line with what was found in Howland et al [11]. Direction of wake deflection depends on numerous conditions, and based on these experiments one of those parameters is downstream position from wind plant entrance.

The wind plant wake characteristics also depend on the radial position, $r$. Figure 4.4 shows the streamwise mean velocity contour plots in a polar coordinate system, with the origin placed at the center of the Coriolis tank. In addition to wake de-
Figure 4.3: The streamwise velocity, \( u \), of the 12 turbine array case in Cartesian coordinates.

By downstream position, there are asymmetric characteristics depending on radial position, including stronger wake recovery in row III (larger radial position), as well as larger wake velocity deficits in row I. It is also apparent that the wake lengths and widths are greater at row I, decreasing moving from II to III. All of these observations lend to the statement that there are radial dependent wake characteristics in a wind plant when Coriolis effects are introduced.

Introducing Coriolis forces to the wind plant means inducing another component to the mean flow velocity. Figure 4.5 is the contour plot of the average \( v \) component.
Figure 4.4: The streamwise velocity, $u$, of the 12 turbine array case in polar coordinates. The case of a single turbine is inset to better show the deflections of the 12 turbine array case.

of the flow velocity, spanwise velocity, at hub height. As expected, there is a strong $v$ component at the entrance of the plant from $0D$ to $5D$. This is the induced Coriolis forcing on the flow. Moving through the plant this component decreases and comes to a stop between $5D$ and $10D$. At this position is when the $v$ component begins to reverse directions, becoming more pronounced at $15D$ and further. This is due to the large filter view, and the area of coverage the experiments take up on the platform. Additionally, there is a faint sign reversal at $\theta = 1.3$ in the wakes of the turbines, before the background flow around the wakes have reversed. This reverse
Figure 4.5: The spanwise velocity, \( v \), of the 12 turbine array case in polar coordinates.

In sign of the spanwise velocity in the wakes explains why we see a stronger wake deflection at this \( \theta \) location in figure 4.4.

The wake center line is tracked by finding \( \partial u / \partial x = 0 \) in each index of the \( u \) velocity matrix. Figure 4.6 displays the radial deflection from the initial turbine position of each row. From 0D to 3D the centerline of the wakes are fairly straight, there is little deflection from the first turbine’s position. This is confirmed in column \( a \) of turbine wakes in figure 4.4. The observed clockwise deflection in figure 4.3 was the wake of those turbines following the rotational flow direction. From 3D to 6D is
the wake centerline of turbines in column \( b \). Here a left or anti-clockwise deflection is observed from the turbines radial position. This anticlockwise deflection is seen in the \( 6D - 9D \) region as well as the \( 9D^+ \) region. There is an additional offset in row 1 centerline starting around \( 6D \), this offset could be due to the fact that row 1 is the first row to see the incoming spanwise velocity component.

To explain the deflection of wakes, we can use the balance in equation 2.1. From this momentum equation and components of the Coriolis force, equation 2.2, van der Laan stated that in regions of slowed flow, the Coriolis force term turns the wake to the left, and in regions of wake recovery the Coriolis force deflects wakes right. When this theory is compared to the results of these experiments, a leftward wake deflection is not seen in regions of slowed velocity. The opposite is observed; in regions of strong wake recovery, a leftward deflection is observed. The reason for this is when the Coriolis force is considered in context of a balance between other forces, the deflection results from the dominating force in the balance, not necessarily the sign and value of the Coriolis force alone. So when the deflection is discussed as a result of a balance between Coriolis forces, pressure forces, and Reynolds stresses, the regions of wake recovery are dominated by pressure forces because the Coriolis forces will get smaller, resulting in an anticlockwise deflection. This theory is explained further in Chapter 2.

Figures 4.7, 4.8, and 4.9 plot the velocity profiles of rows I, II, and III respectively. Three profiles are taken behind each turbine in the plant and are organized by the rows. The profiles were taken at \( 0.5D, 1.5D \) and \( 2.5D \) behind each turbine to visualize the wake development of each turbine and to make quantitative observations about wake recovery and the merging and impingement.
Figure 4.6: Wake center line tracking of each row in the 12 turbine $3D \times 3D$ plant. Turbines are located at $0D, 3D, 6D$, and $9D$.

Figures 4.7, 4.8, and 4.9 showed that behind turbines $a$ the velocity profiles were decreasing in velocity. Based on the theory of force balances on the turbine wake, the decrease in velocity results in a dominating Coriolis force and thus a clockwise deflection. In figure 4.6 behind turbine $a$ there was little to no deflection, indicating that the wake in this region was balanced by all the forces. This indicated that the Reynolds stress played an important role in the balance of these forces and influenced the direction of wake deflection. Referencing figures 4.7, 4.8, 4.9 again, behind turbines $b$, $c$, and $d$ the velocity profiles increased, indicating a region where the Coriolis force decreased and the pressure force dominated, and resulted in an anti-clockwise wake deflection behind these three turbines. This was confirmed in figure 4.6 behind turbines $b$, $c$, and $d$ where a strong anti-clockwise deflection was observed. This indicated that in the regions of wake recovery, the dominating
Figure 4.7: Velocity profiles at 0.5D, 1.5D and 2.5D behind each turbine in row I of the wind plant.

force was the pressure, causing anti-clockwise deflection. Additionally, the regions of decreasing velocity is theoretically dominated by Coriolis and would cause a clockwise rotation, but the results show that there was an additional influence by the Reynolds stress.

From figure 4.7 the profile shapes change with turbine location. Turbine Ia has a Gaussian curve shape. Turbine Ib has a profile that reflects the form of a bi-modal distribution. The second smaller peak in the profiles of turbines in the b column comes from the turbine wake ahead of it, indicating strong wake impingement. Turbines Ic and Id are similar to one another, both making a slight return to a Gaussian distribution with the addition of a positive skew. This is likely the dissipation from the interactions between the the first two turbines ahead causing wake merging within the rows. The progression of profile shapes of row I can be
Figure 4.8: Velocity profiles at 0.5D, 1.5D and 2.5D behind each turbine in row II of the wind plant.

seen in rows II and III. These profiles confirmed the interactions between the wakes of the turbines in the plant, showed that the wake of the first turbine impacts the rest of the turbines proceeding it, even in the presence of Coriolis.

Wake recovery is different through each turbine in a row, and there is also a difference based on radial position. Figure 4.7 contains the profiles of row I, turbine a profiles show recovery starting to happen between 1.5D and 2.5D. Turbine b has variation in recovery across the wake. In the larger peak, wake recovery appears to happen between 1.5D and 2.5D. The smaller peak decreased in velocity values after 0.5D. Turbines c and d show a similar trend, velocity values decreased after 0.5D. Investigation of row II presents similar trends to row I. Row III also shows similar trends except in turbine b. Turbine IIIb decreased in velocity values after 0.5D in both peaks of the profile. This is possibly due to higher velocity speeds on
Figure 4.9: Velocity profiles at $0.5D$, $1.5D$ and $2.5D$ behind each turbine in row III of the wind plant.

the outside of row III, encouraging more wake recovery than the inner two rows.

Figure 4.10 is the $\overline{uv'}$ Reynolds stress component contour. This contour plot is a map of the Reynolds Stresses taken at hub height of the 12 turbine $3D \times 3D$ spacing experiment. Asymmetric stresses are seen in the plant. The magnitude of the stresses are stronger in back of the plant when compared to the stresses developed at the front of the plant. There is also evidence of a slight radial dependency of this wake behavior. In column $a$, the turbine closest to the center of the platform, in row I, develops a slight imbalance between the negative and positive stresses. As the radial position in column $a$ increases, the stresses are less asymmetric. The turbine in the furthest radial position, row III, developed relatively balanced stresses. Additionally the maximum magnitudes of the Reynolds stresses are imbalanced, with the positive shear stress higher in magnitude. This all suggests that the Coriolis

\[ \overline{uv'} \]
forces influenced the development of Reynolds stresses, and caused imbalances and asymmetry.

Figure 4.10: $\vec{u}'\vec{v}'$ contour plot in polar coordinates. The origin is located at the center of the tank. $r$ is normalized by the rotor diameter.
Investigations of Coriolis effects on wind turbines and wind plants have been limited to numerical research. Due to the complexity that comes with properly recreating Coriolis effects on a scaled set up, experimental methods have not been done yet. The research presented here not only yields quantitative information about the impact of Coriolis effects on a wind plant’s dynamics, it opens the door to a new method of research for scaled wind plant experiments.

One of the major questions surrounding Coriolis forces and wind plants was the direction of wake deflection. The experiments performed, showed that it was not a trivial answer. In the single turbine experimental case, deflection of the wake was not seen in the radial coordinate velocity contours, thus Coriolis forces have negligible impact on a single turbine. For wind plants, the deflection was more pronounced in the far wake regions. In the $3D \times 3D$ farm case the direction of deflection was dependent on a turbines downstream position from the farm entrance. This was observed in the velocity contours and centerline tracking of the farm. These deflections were caused by an imbalance between the pressure forces, Coriolis forces, and some influence by Reynolds stresses. In regions of wake recovery, the pressure force outbalances the Coriolis force, and the wake was deflected anti-clockwise. Theory
suggests that the wakes would be deflected clockwise in regions of decreasing velocity, where Coriolis forces dominate. Behind the first turbine, velocity decreases and there is no visible deflection. This suggests that the Reynolds stresses also play a role in the wake deflection within a wind plant.

In the velocity profiles of the farm, the shapes of the profiles were different behind each turbine. Due to the Cartesian arrangement of the farm in a rotational reference frame, the impinging wakes of the turbines cause the variations in profile shapes. The development of profile shapes are consistent through each row of the farm.

The Reynolds shear stress developed in the farm are influenced by Coriolis, and this is seen in the development of stresses at the back of the farm. At the first turbines of the farm, the stresses aren’t as strong and are relatively balanced. Towards the back of the farm, the stresses develop in much higher magnitudes. The magnitudes between the positive and negative shear stresses are imbalanced as well. The highest positive stress magnitude is larger than the negative shear stress magnitude, suggesting that Coriolis influences the development of these Reynolds Stresses and depends on the downstream position from the farm entrance.

The research discussed was the first experimental scale study of Coriolis influence on wind turbine wakes within a wind plant. These experiments provided a new method of studying the mesoscale flow of a wind plants subjected to Coriolis forces. As wind turbines grow larger, and further into the ABL, a better understanding of the physics in these flows are necessary. More wind plants are being installed at higher latitudes, and power density maps show high potential spots near the poles, where Coriolis forces are strongest. Building a strong foundation of the understanding of Coriolis forces and wind plants will help develop models for efficient wind
energy production and wind plant performance. The large-scale that wind energy has grown to means that any advancement of knowledge has the potential to compile and add up to substantial changes on a global scale.
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