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Mechanics of Canopy Turbulence

by

Hawwa Falih Kadum

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

Doctor of Philosophy
in
Mechanical Engineering

Dissertation Committee:
Raúl Bayoán Cal, Chair
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Portland State University
2020

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Abstract

Large canopies interact with the atmospheric boundary layer (ABL) and alter transport of matter, energy, and momentum in accordance to their morphology. Canopy structure influence on turbulent processes can be utilized to achieve favorable interactions. Wind farm and forest canopies spatial arrangement is investigated in this work. Momentum fluxes investigated in a horizontal axis wind turbine (HAWT) array showed the existence of gusts of wind transported both from ABL above the canopy and the unperturbed flow below the canopy through sweep and ejection events. A new wind farm arrangement in which clusters of vertical axis wind turbines (VAWT) are collocated with HAWTs is proposed to enhance power harvested per unit area. An aligned collocated arrangement is found to increase power production by 3.5%. This approach opens possibilities to further optimize the collocation layout and determine the arrangement that extracts most power. Other considerations in terms of renewable energy production are focused on advancing offshore wind farms design by considering their wake flow intermittency due to its consequence in increasing dynamic loading on the turbine structure. It is found that pitch motion increases intermittency in floating wind turbine wake up to five turbine diameters downstream the turbine and shorter in highly turbulent flow. Furthermore, a heterogeneity parameter is developed to measure spatial variations in canopies. The parameter proved successful in measuring heterogeneity of forest canopies with various spatial arrangements. Momentum advection was found to increase up to 14 times that of a homogeneous canopy. Power law relation is determined between heterogeneity parameter and momentum advection. These findings have implications in determining environmentally viable forest management and

enhanced weather forecasting. Understanding the dynamics between turbulent processes and spatial variations in canopies is of essence to exploit them in sustainable development.

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Chapter 1

Introduction

Research attention is given to sustainable development to reduce greenhouse gas effects by reducing CO₂ future emission and CO₂ current and future concentration mainly through investing in renewable energy and forestation [Allen et al., 2010, Baldocchi et al., 1988, Borg et al., 2014, Cox et al., 2000, Markfort et al., 2018, Shires, 2013, Sims et al., 2003, Weathers et al., 2001]. Increasing the use of fossil fuel and deforestation together have raised atmospheric CO₂ concentration by about 25% over the last 150 years [Akbari, 2002]. Efforts have been employed to reduce our fossil fuel consumption as it is a prime contributor to CO₂ emission, 39% of the 6 billion metric tons emitted annually to generate electricity in the US [Lindenberg, 2009]. Wind energy represents a promising candidate for an alternative renewable and clean source of energy [Bohrer et al., 2009]. Wind plants and forest canopies introduce turbulence and alter local temperature and heat flux profiles. The boundary layer close to and within a canopy is spatially and temporally varying due to the interaction between the mean flow and individual canopy elements, see figure 1.1. Fluxes of matter, momentum, and energy are altered accordingly. The variations occur on many scales, from that around individual canopy elements (leaves and branches in forests and blades in wind turbines) to the canopy scale caused by elements density [Harman et al., 2016, Poggi and Katul, 2008]. See figure 1.2.

Figure 1.1: Computed profile of air temperature within and above a deciduous forest using CANOAK model. The figure is adapted from [Baldocchi et al., 2002].

The aforementioned canopy-atmosphere aerodynamics creates a complex flow regime that is challenging for micrometeorologist [Desmond et al., 2017]. Despite progress in the past few years, further advancement is needed in increasing contribution from wind plants to global energy supply, canopies interaction with atmospheric boundary layer to develop advanced weather prediction models and air quality forecasting, and characterizing the movements and fluxes of the flow past these canopies [Belcher et al., 2003].

1.1 Wind Energy

Energy demand is expected to increase 3-5 times by 2050 due to population growth arising environmental concerns [Dincer, 2000]. Numerous efforts are put towards wind plants power production maximization by optimizing their spacing [Ali et al., 2018, Stevens et al., 2016], layout [Bossuyt et al., 2018, Hamilton et al., 2015, Tian et al., 2018], design [Bal-

Figure 1.2: Vertical profiles of MKE flux K_{xy} (top row) and wind veer $\langle \gamma \rangle_{xy}$ (bottom row) within and above wind turbine canopies of several different densities ($s_1 - s_7$) operating in unstable, neutral, and stable thermal stratification regimes presented from left to right, respectively [Cortina et al., 2017b].

duzzi et al., 2017, Zheng and Lin, 2017], and wake recovery [Aghsaee and Markfort, 2018, Rockel et al., 2017].

The wind energy contribution to the overall electricity production strives to reach 20% by 2030 [DOE, 2008]. Consequently, wind plants are covering ever increasing land areas [Meyers and Meneveau, 2012]. This scenario imposes two challenges to scientists and

climatologists. First, investigating possibilities to expand wind plants in number and size to reach the 20% goal. Second, with the wind plant expansion, it becomes of scientific interest to quantify the effects of energy extraction and atmospheric structure on each other by examining their interactions. In regards to the former, offshore wind plants are of increasing interest as a promising renewable energy source with vast, close to populated areas space and high wind speeds to harvest [Junginger et al., 2004, Koh and Ng, 2016, Rockel et al., 2017]. Denmark was the first to build an offshore wind plant in the world in Vindeby in 1991, see Figure 1.3. It wasn't until 2009 when the first floating offshore wind farm Hywind was launched in Scotland. It consists of five floating turbines with a total capacity of 30 MW. Offshore wind plants are still maturing compared to on land installed wind plants. One significant concern is the aerodynamic loads on the turbines due to their unrestrained platforms. How does the movement of these platforms alters the wake flow and the power output are matters to need to be investigated.

Figure 1.3: The first commercial offshore wind plant in Vindeby, Denmark [Nikolaos, 2004].

In addition to offshore wind plants development, numerous efforts are invested in reducing the area occupied by wind plants via enhancing their wake recovery. Various layouts have been presented to optimize power extracted per wind plant area [Ghaisas et al.,

2017, González et al., 2017, Tian et al., 2018]. Research in this area shows that horizontally staggered wind turbine placing can have a 10% to 35% [Chamorro et al., 2011, Stevens et al., 2014] increase in overall power output. In staggered arrangements, the wake is similar to that of a single wind turbine, more uniformly distributed compared to an aligned wind turbine array, and features lower turbulence intensity [Chamorro et al., 2014]. The unique wake characteristics have been investigated both experimentally and numerically [Astariz et al., 2018, Hamilton et al., 2015, Porté-Agel et al., 2013]. For example, the experimental work of Chamorro et al. [2011] revealed the benefits of staggered configurations in terms of momentum transfer and vertical transport [Cal et al., 2010, Calaf et al., 2010, Hamilton et al., 2012].

Following the evidence of these results, enhancement in energy extraction induced by horizontal heterogeneity urged the examination of vertically-staggered horizontal axis wind turbines (HAWT) configurations. The idea of vertically-staggered wind plants was introduced by Chamorro et al. [2014] in a wind tunnel experiment where rows of HAWTs of different heights and rotor diameters were alternated. The plant layout led to unique flow interactions not observed in the homogeneous plants. Reduced levels of turbulence were observed as well as a uniform flow structure compared to its homogeneous counterpart. While Zhang and Stevens [2018] work showed similar production for aligned and vertically staggered plant configurations, Vested et al. [2014] reported that kinetic energy production drop across the wind plant was only 29% in the vertically staggered array compared to 43% for the homogeneous case. More recently, Xie et al. [2017] suggested collocating VAWTs and HAWTs to harvest the uninterrupted flow below the HAWT rotor tips using the smaller VAWTs. Xie et al. [2017] conducted an LES investigation in which the space between HAWTs is occupied with VAWTs, each HAWT being surrounded by 20 VAWTs. The

collocated wind plant energy production increased by 32%. Perhaps more importantly, the production of the single HAWT increased by 10% indicating faster wake recovery due to topography change. These findings suggest a new approach to wind power harvest maximization that might allow for tighter wind turbine arrangements thanks to shorter wakes behind the HAWTs. Given the reduction in plant size that results from faster wake recovery of the HAWT when collocated with VAWTs, it is of interest to investigate the flow characteristics of these plants and the possible ways to optimize it. The smaller size of VAWTs makes them an attractive option when land availability is of concern [Abkar, 2018, Abkar and Dabiri, 2017, Dabiri, 2011, Kadum et al., 2018]. Recent studies have shown a power production increase when VAWTs are set in a counter-rotating manner [Hamilton and Cal, 2015, Parneix et al., 2016], also highlighting the potential benefits of grouping VAWTs in clusters of particular arrangements to enhance the performance of each wind turbine [Hezaveh et al., 2018]. Hezaveh et al. [2018] reported a 10% increase in the power produced by a single VAWT when placed within a cluster of turbines in comparison to conventional individual turbine arrangements.

1.2 Forest Canopies

The flow above a surface is altered by its spatial heterogeneity [Avisar, 1991, Garratt, 1978, Pope, 2000]. In atmospheric sciences, models used for weather predictions are based on the Monin-Obukhov similarity theory [Monin and Obukhov, 1954]. The theory is based on the assumption of momentum and energy balance that holds for flat and homogeneous surfaces [Babić and Rotach, 2018]. Atmospheric sciences use the similarity theory in modeling heterogeneous surfaces. The justification in that case is either strong turbulence mixing blends heterogeneity effects above a certain height from the surface,

referred to as the blending height, or the vertical scales caused by surface heterogeneity are small compared to the horizontal scales [Bou-Zeid et al., 2004, Brutsaert, 1998]. In the presence of important spatial heterogeneity, the similarity theory is less accurate [Avissar, 1992, Brutsaert and Parlange, 1992], where the mean flow recirculation becomes the main blending mechanism. Furthermore, the atmospheric models use simulations with grid sizes that are often larger than the smaller scale heterogeneity and consequently do not capture their effects [Beare, 2014, Margairaz et al., 2020, Patton et al., 2005, Wyngaard, 2004].

Spatial heterogeneity becomes even more important and challenging when dealing with forest canopies. Its importance stems from the fact that forests are one of the largest canopies encountered by atmospheric flows in terms of cover areas, and perhaps more importantly because of the significant drag they introduce as well as the active microclimate they create within the canopy layer [Finnigan, 2000, Poggi et al., 2004a, Tajchman, 1981]. The challenge of incorporating forest heterogeneity into atmospheric science models is related to the broad range of scales at which this heterogeneity occurs from scales as small as the tree branches and height to gaps and patches on the order of canopy boundary layer height [Bohrer et al., 2009, Bou-Zeid et al., 2007, Collins and Avissar, 1994]. Not only it is challenging to quantify the heterogeneity related scales of motion added to the flow in this case, but also the changes occurring at the smallest scales within the forest canopies have been shown to lead to changes on significantly larger scales in the boundary layer above the canopy [Finnigan, 2000, Lo, 1990]. Evaluating the heterogeneity impact from various scales within the canopy layer and their connection to the ABL is a necessary complement to numerical weather prediction and atmospheric science models.

It has been shown that horizontal heterogeneity leads to time-averaged spatial variation

in the mean velocity field. The time-averaged variations create momentum flux that has been identified by Wilson and Shaw [1977] and called dispersive stress. The dispersive stress is added to Reynold shear stress to obtain the total stress. Early studies in rough surfaces and forest canopies determined the contribution of dispersive stress negligible compared to the Reynolds shear stress Mulhearn [1978], Perry et al. [1987], Raupach et al. [1986]. Recent studies, however, found dispersive stresses at the entrance to a forest canopy to influence momentum transfer and create a vortex along the leading edge [Moltchanov et al., 2011, Tischmacher and Ruck, 2013]. These vortices form a momentum wave capable of damaging trees within a stand and greatly enhance gas and particle ejection into the ABL [Conan et al., 2015, Tischmacher and Ruck, 2013]. Evaluating dispersive stresses in heterogeneous canopies

Descriptions of wind flows within forest canopies have been published since the late 1800's [Metzger, 1893]. Early studies focused on flow characteristics within continuous forests which produced a strong dependence on local forest parameters such as tree species and age. Efforts to remove the influence of local effects by normalizing forest canopies in a wind tunnel setting demonstrated the potential of model setups to recreate forest dynamics. The model canopies used in these studies were scaled predominantly by the mean drag force exerted by the bluff body [Meroney, 1968, Raupach et al., 1986]. Various structures ranging from plastic trees and cubes [Desmond et al., 2014, Hamed et al., 2017, Lee and Lee, 2012, Stacey et al., 1994] to metallic mesh and fractal trees [Aubrun and Leidl, 2004, Bai et al., 2012, Conan et al., 2015, Coudour et al., 2016] were employed with tree position determined empirically. Normalizing model canopies in these studies facilitated detailed investigations of various turbulent flow components including quantification of momentum transfer, turbulent kinetic energy, and shear stress. Comparison of models from wind

tunnel studies to data obtained in forest stands improved the knowledge about canopy flow dynamic and lead the development of mixing layer analogy to describe the unique effects of canopy composition on the ABL [Finnigan, 2000, Gardiner, 1994, Raupach et al., 1996]. The relevance of the mixing layer analogy was related to stand density to replace experimental dependence on empirical roughness lengths [Poggi et al., 2004b]. Incorporating tree distribution within a stand of given density further enhanced the agreement between wind tunnel and field data by accounting for horizontal heterogeneity [Raupach et al., 2006]. A notable advancement in forest models was made by Rodrigo et al. [2007] where reticulated foam was used to produce an isotropic canopy with comparable leaf area density to real forest. Following this study, models made of reticulated foam were shown to accurately reflect tree dynamics in terms of the total drag, mean velocities in three dimensions, turbulent kinetic energy, shear stress, and energy spectra [Gromke and Ruck, 2008]. Reticulated foam cones mounted to wooden trunks were used in a canopy designed to accurately reflect momentum and pressure losses for quantification of the shear stresses above the canopy [Gromke and Ruck, 2018]. The design of this canopy model marks a departure from previous models as it is based primarily on geometric and dynamic similarity to tree species rather than average quantities such as drag or velocity profile.

The goal of the current study is to first: develop a measure of spatial heterogeneity that accounts for various types of canopy variations. Secondly, the heterogeneity measure is related to momentum transport above and within heterogeneous forest canopies that consist of alternating patches and gaps with special emphasis given to mean flow terms. Various combinations of gap and patch sizes are testes in a wind tunnel a long with a continues patch case with no gaps all manufactured using reticulated foam. Control volume analysis is used to obtain the bulk effect of the terms in the momentum equation. Spatial hetero-

geneity measure is tied to flow related heterogeneity to propose a heterogeneity parameter that encompasses both factors. The relation between momentum transport terms and heterogeneity parameter is intended to be used in models to account for spatial variations in canopies.

In summary, this work is intended to help answering questions related to wind plant and forest canopies. The possibility of increasing power production in wind farms by altering their canopy arrangement is examined. Turbulent fluxes and wake recovery of different wind plant arrangements and wind turbine designs are studied. Offshore wind turbine wake flow is investigated herein to shed light on the effect of the additional degrees of freedom experienced by floating wind turbines by conducting intermittency analysis as a way to further develop wake models and estimation of dynamic loads experienced by the turbines. Using new approaches to determine the intermittency in the wake of pitching wind turbines and comparing the results to conventional structure functions analysis. In wind plant arrangements, Large eddy simulations (LES) are employed to investigate the collocated wind plants (CWP) kinetic energy budget compared to that of standard wind plant (SWP). Two collocation arrangements are examined to identify the configuration that could best enhance power harvesting. The VAWTs are added as clusters of three turbines either aligned or staggered with respect to the HAWTs array. First, the harvested power per characteristic HAWT is computed and compared for the three arrangements. Then, using control volume analysis, the mean flow statistics and mean kinetic energy budget analysis is conducted for a characteristic HAWT describing the flow features of each configuration. The description highlights the features that enhance wake recovery and power harvesting improvement. Forest heterogeneity is described through developing a heterogeneity parameter that is able to measure the heterogeneity level of a forest canopy regardless of the

type of heterogeneity present. A geometric heterogeneity index is developed using lacunarity analysis and tested using control volume of momentum transport equation. Another measure is proposed that captures flow heterogeneity, the two factors are then combined into one parameter. The relationship of this parameters to the flow in different canopy layers is examined. The similarities and difference between the flow at each canopy layer is highlighted.

The dissertation is organizes as follows: Chapter 2 presents the theory behind each analysis used in this work. Chapter 3 describes experimental methods and simulation suits used to obtain the data sets. The results are presented and discussed in Chapter 4. Conclusions followed by outlook are depicted in Chapter 5 and Chapter 6, accordingly.

Chapter 2

Theory

Details about the theories behind the analysis used to obtain results is described here. The transport of momentum and kinetic energy is of central importance in the context of boundary layer flow and scalar transport and exchange within a canopy. To provide a framework for discussion, a simplified momentum transport equation is presented as,

$$\underbrace{U_j \frac{\partial U_i}{\partial x_j}}_{I_a} = - \underbrace{\frac{1}{\rho} \frac{\partial P}{\partial x_i}}_{II_a} - \underbrace{\frac{\partial \overline{u'_i u'_j}}{\partial x_j}}_{III_a} + \underbrace{F_i}_{IV_a}; \quad (2.1)$$

where upper case and overbar ($\overline{}$) indicate ensemble averaged quantity, while fluctuating quantities are indicated with a prime (ϕ'). U_i is a streamwise, spanwise, or vertical velocity component. Subscripts i and j are x, y, z for streamwise, vertical, and spanwise directions, respectively. P is pressure and ρ is fluid density. The momentum advection (I_a) is on the left-hand side of the equation. The right-hand side terms are respectively pressure term (II_a), stress gradient term (III_a), and body forces (IV_a). Multiplying the above equation by the mean flow velocity yields the Mean kinetic energy equation as;

$$\underbrace{U_j \frac{\partial \frac{1}{2} U_i U_i}{\partial x_j}}_{I_b} = - \underbrace{\frac{1}{\rho} U_i \frac{\partial P}{\partial x_i}}_{II_b} - \underbrace{\frac{\partial U_i \overline{u'_i u'_j}}{\partial x_j}}_{III_b} + \underbrace{\overline{u'_i u'_j} \frac{\partial U_i}{\partial x_j}}_{IV_b} - \underbrace{\mathcal{F}_i}_{V_b}, \quad (2.2)$$

The left-hand side consists of the convection of mean kinetic energy (I_b). The right-hand side terms are: the rate of energy added to the flow by the mean pressure gradient (II_b), power associated with the energy flux (III_b), the production of kinetic energy (IV_b), and power extraction by the turbine itself (V_b). Terms associated with viscous diffusion and dissipation have been omitted on the grounds that these terms are negligible compared to other terms.

2.1 Quadrant Analysis

The mechanisms by which the flux and production terms act on the mean flow can be examined by conditional sampling of the Reynolds stress [Hamilton et al., 2012, Nolan et al., 2010, Raupach, 1981, Roussinova et al., 2009]. The method of decomposition consists of binning the velocity fluctuations, obtained by subtracting the mean velocity U_i from the instantaneous velocity as $u'_i = u_i - U_i$, by their respective signs as shown in Fig. 2.1. Here, the coordinate system is considered where u , v , and w represent the streamwise, wall-normal, and spanwise fluctuating velocity components, respectively. The stresses are computed for each of these conditions resulting in four types of events designated as follows: outward interaction Q_1 , ejection Q_2 , inward interaction Q_3 , and sweep Q_4 .

The average stresses for each event are traditionally decomposed by temporal fluctuations of the velocity components. In applying conditional sampling to spatial PIV data,

Figure 2.1: Conditional sampling of the fluctuating component of velocity

the averaged shear stress for each quadrant conditionally sampled by $\overline{u'v'}$ is defined as,

$$\overline{u'_i u'_{j_k}} = \frac{1}{N} \sum_{m=1}^N I_k(u', v') u'_{i,m} u'_{j,m}, \quad (i \neq j), \quad (2.3)$$

an ensemble of N samples in quadrant k . The function, $I_k(u, v)$ is defined as,

$$I_k(u', v') = \begin{cases} 1, & \text{if } (u', v') \text{ is in quadrant } k \\ 0, & \text{otherwise} \end{cases} \quad (2.4)$$

where $k = 1, 2, 3, 4$. This definition is such that the total shear stress is given by,

$$\overline{u'_i u'_j} = \sum_{k=1}^4 \overline{u'_i u'_{j_k}}. \quad (2.5)$$

Normalizing the event-averaged stresses by the total stress, the stress fractions are obtained for each quadrant as are given by,

$$S_{u_i v_j} = \frac{\overline{u'_i u'_{jk}}}{\sqrt{\overline{u'^2_i u'^2_j}}} \quad k = 1, 2, 3, 4. \quad (2.6)$$

Due to the prominence of ejection and sweep events in boundary layer flows, the relative importance of these events is examined using the difference between their stress fractions as given below,

$$\Delta S_{u_i u_j} = S_{u_i u_j, 4} - S_{u_i u_j, 2}. \quad (2.7)$$

For more complex flows, where regions of dominant events may be unclear, the exuberance E includes contributions of all quadrants and is defined in [Shaw et al., 1983] as

$$E_{u_i u_j} = \frac{S_{u_i u_j, 1} + S_{u_i u_j, 3}}{S_{u_i u_j, 2} + S_{u_i u_j, 4}}. \quad (2.8)$$

The exuberance is a ratio of the upward rate of momentum transport to the downward rate of momentum transport (when considering the $\overline{u'v'}$ stress) and provides a measure of the relative importance of interactions and sweeps/ejections.

The complexities that arise in the canopy of a large wind turbine array due to the motion of the active blade elements call for careful consideration of the out-of-plane stresses $\overline{u'w'}$ and $\overline{v'w'}$. One could employ the same conditional sampling techniques discussed herein on each of these stresses, but the quadrant motions become difficult to interpret. Instead, because of the prominence of the $\overline{u'v'}$ stress is expected due to the bulk motion of the flow field, the Reynolds shear stresses (RSS) $\overline{u'w'}$ and $\overline{v'w'}$ are considered by conditioning on

$\overline{u'v'}$. The behavior of all shear stress components in the context of upward or downward transport of momentum are characterized with this definition.

2.2 Structure Function

According to self similarity theory introduced by Kolmogorov in 1941, (K41) hereon, for high Reynolds number, incompressible, and stationary turbulence, the small-scale motions are statistically isotropic and the distribution of the velocity increments between two points in space is determined by a scale l [Wang et al., 1996]. Moments of these velocity increments are given by,

$$B(R)^q = \langle (u(x+R) - u(x))^q \rangle = \langle \delta_R u(x)^q \rangle = \langle \epsilon \rangle^{\frac{q}{3}} R^{\frac{q}{3}} f_q(\mathcal{R}_R). \quad (2.9)$$

where R is separation distance between two data points that translates to scales using Taylor hypothesis [Taylor, 1938]. The Reynolds number is defined as $\mathcal{R}_R = \epsilon^{-1/3} R^{4/3} / \nu$, where ϵ and ν are the dissipation of mean kinetic energy and the kinematic viscosity, respectively. For $\mathcal{R}_R \gg 1$, the distribution of velocity increment is independent of ν [Boffetta et al., 2008, Pope, 2000], and it is described as:

$$B(R)^q \approx \langle \epsilon \rangle^{\frac{q}{3}} R^{\frac{q}{3}}. \quad (2.10)$$

In the Kolmogorov refined theory proposed in 1962, (K62 hereon), the dissipation of turbulent kinetic energy ϵ was considered as a function of scale [Oboukhov, 1962, Oboukhov and Kolmogorov, 1962]. The variation of dissipation was accounted for in the scaling exponent ξ where $B(R)^q \sim R^{\xi(q)}$, where the exponent $\xi(q)$ contains $q/3$ plus intermittency correction Δ . In the refined theory, Kolmogorov [Oboukhov and Kolmogorov, 1962] and

Oboukhov [Oboukhov, 1962] proposed the log-normal model in which the intermittency correction Δ is defined as;

$$\xi(q) = \frac{q}{3} + \Delta, \quad (2.11)$$

$$\Delta = -\frac{\mu}{18} q (q - 3), \quad (2.12)$$

where μ is the so-called intermittency coefficient [Renner et al., 2001]. Based on equation 2.11, the deviation of the actual scaling exponent from the straight $q/3$ line represents the intermittency correction Δ and can be used as an approximated measure of intermittency [Ali and Cal, 2019]. Several models have been developed to calculate $\xi(q)$ with respect to intermittency coefficient μ [Renner et al., 2001]. However, the extended self similarity (ESS) model introduced by Benzi [Benzi et al., 1993] offers the possibility of estimating the scaling exponent $\xi(q)$ from the slope of a structure function of order q with respect to its 3rd order structure function [Ali et al., 2016a]. The third order structure function does not have intermittency correction, which can be shown analytically through examining Kolmogorov 4/5 law. Assuming local homogeneity and isotropy, from the Navier-Stokes equations the following equation is obtained

$$B(R)^3 = -\frac{4}{3}\varepsilon R + 6\nu \frac{d}{dR} B(R)^2, \quad (2.13)$$

the second term on the right hand side of the equation is small and can be neglected. Hence, the third order structure function has a linear relationship with scales. This leads to $\xi(3)=1$. Based on equation 2.11, the latter fact makes the intermittency correction $\Delta = 0$. Using this, Benzi proposed plotting a q^{th} order structure function that contains an intermittency correction against the third order structure function having a unity scaling exponent $\xi(3)$. The slope between the two structure functions will therefore directly yield

$\xi(q)$, see [Benzi et al., 1993] for more details. The first scaling exponent is referred to as the Hurst exponent $\mathcal{H}$. For a monofractal (non-intermittent) system, the Hurst exponent can be used to obtain a theoretical scaling exponent as $\xi(q) = \mathcal{H}q - 1$. The line generated when plotting the theoretical scaling exponent and the order q can be used to calculate the intermittency. This is obtained by plotting the theoretical scaling exponent and the actual scaling exponent is yielded using structure functions; the deviation of the scaling exponent from the theoretical is the intermittency [Ali and Cal, 2019, Schmitt et al., 2009].

2.3 Hilbert-Huang Transform

Hilbert-Huang transform (HHT) returns instantaneous frequency corresponding to local amplitudes, thus it is associated with unsteady and nonlinear signals [Krishnan and Samiappan, 2018]. HHT is used in mechanical engineering [Chen et al., 2004, Elbouchikhi et al., 2017, Loutridis, 2004, Merainani et al., 2017], acoustics [Loutridis, 2005, Sun et al., 2017], meteorology and climate [Coughlin and Tung, 2004, Jánosi and Müller, 2005, Salisbury and Wimbush, 2002], and in detection and localization of damage [Banerji et al., 2017, Han et al., 2017, Moughty and Casas, 2017, Zhang et al., 2017]. The energy-frequency-time representation of HHT is of significant advantage in turbulent flows data analysis. The local energy contained has been exploited in coherent structure and scale interactions in turbulent flows [Zhu et al., 2016]. Numerous works have been conducted dealing with turbulent flow scales via their energy content, however, they are usually conducted using Fourier and wavelet transforms. Despite the usefulness and mathematical logic of these methods, they are limited to small nonlinearities, and they lack the ability of revealing the physical meaning of a nonlinear process [Huang et al., 1999]. Hilbert-Huang transformation (HHT) is a method introduced to process nonlinear and unsteady

signals [Huang et al., 1998]. For a system with overlapping events, the time series usually contains multiple scale (multi-scale signal). The general approach into decomposing the multi-scale time series into signals with approximately one scale (narrow band of frequencies) is to define a characteristic length scale. The Fourier spectral analysis defines the characteristic length scale as the length of sine or cosine wave [Schmitt et al., 2009]. The characteristic scale for the EMD analysis is defined as the distance between any two successive maxima (or minima) points in the original time series, this is done by identifying all the minima and maxima peaks in the time series, then finite number of characteristic length scales are found from the different distances between the signal peaks. Based on these characteristic length scales, the signal is decomposed into a finite number of data sets called intrinsic mode functions (IMF) and a residual. The first IMF contains the highest frequencies [Huang et al., 1998, Schmitt et al., 2009]. Each IMF approximately represents a mono-scale (represents approximately one frequency that corresponds to one event of the events happening in the original multi-scale signal). An IMF must satisfy two conditions:

- 1- The number of extrema (or minima) equals the number of zero crossing.
- 2 -The IMF mean must be zero.

Figure 3 illustrates a velocity fluctuations, u' , time series and one of its IMFs obtained using EMD. The figure highlights the conditions met by the IMF signal compared to the original velocity signal.

Figure 2.2: Velocity fluctuations time series, u' , and its fourth IMF plotted with their upper and lower envelopes. The IMF has a zero envelop mean, the dashed black line, and the number of extrema peaks is equal to the number of minima peaks.

The methodology of generating IMFs from a signal is by first, decomposing the original signal into a new signal and a residual. The extrema and minima envelopes of the new signals are to be determined; then, the mean of the two envelop is calculated. If the mean is not zero, a second iteration is to take place. In the second iteration, the new signal is decomposed into a newer signal and a residual. The extrema and minima envelopes and their mean are calculated again. If the mean is still not zero, another iteration is carried out and so on until the first IMF has a zero mean. The remaining IMFs are computed the same way [Tolwinski, 2007]. The EMD generates IMFs that correspond to real physical events. However, some of the IMFs are not significant. The way to distinguish the IMFs that represent a physical event is conducting a cross correlation analysis between the IMF and the original time series. The IMFs that show high correlation are the most significant ones. After the decomposition, the result is IMF signals $C_i(t)$ and a residual $r_n(t)$. The subscript i denotes the i^{th} IMF signal. The original signal can be expressed as;

$$X(t) = Re \sum_{i=1}^N C_i(t) + r_n(t), \quad (2.14)$$

where Re indicates real part. Each mode function $C_i(t)$ has an associated Hilbert transform $\widetilde{C}_i(t)$,

$$\widetilde{C}_i(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{C_i(\tau)}{t - \tau} d\tau, \quad (2.15)$$

where t and τ are time and time lag, respectively. The combination of a mode function and its Hilbert transform gives an analytical signal $z_i(t)$ its real part is the mode function C_i , and its imaginary part is the Hilbert transform $\widetilde{C}_i$ [Huang et al., 2008a].

$$z_i(t) = C_i + j\widetilde{C}_i = A_i(t) e^{j\theta_i(t)}. \quad (2.16)$$

The analytical signal of the i^{th} IMF, $z_i(t)$, results in a velocity amplitude A_i and a phase θ_i . When the amplitude is extracted from all (or several) IMFs, it is referred to as A . The aforementioned variables can be calculated as,

$$A_i(t) = \sqrt{C_i^2 + \widetilde{C}_i^2}, \quad \theta_i = \tan^{-1} \frac{\widetilde{C}_i}{C_i}. \quad (2.17)$$

Now, the original signal can be written as,

$$X(t) = Re \sum_{i=1}^N A_i(t) e^{j\theta_i(t)}. \quad (2.18)$$

The energy contained in each IMF, Hilbert spectrum, and instantaneous frequency can be obtained as,

$$H(f, t) = A_i^2(f, t), \quad (2.19)$$

which describes the local energy in time-frequency domain. The energy contained in all

IMFs, Hilbert marginal spectrum, is the integration of Hilbert spectrum over the total number of IMFs as described below [Schmitt et al., 2009],

$$h(f) = \int_0^\infty H(f, t) dt. \quad (2.20)$$

2.4 Joint Probability Density Function

Joint probability density function (JPDF) is a high resolving quantity to investigate correlations between variables. JPDF is discussed here as it is used for detailed analysis of HHT results. JPDFs show the likelihood of two random events occurring at the same time. To understand the fundamental of JPDF, the bivariate normal density basics becomes relevant. For two Gaussian random variables X and Y , two covariants σ_{ii} and their correlation coefficient ρ are defined as;

$$\sigma_x^2 = \sigma_{xx}, \quad \sigma_y^2 = \sigma_{yy}, \quad \rho = \frac{\sigma_{xy}}{\sigma_x \sigma_y}, \quad (2.21)$$

respectively and σ_i is the standard deviation of a certain variable. Accordingly, the general bivariate normal density is then described as [Belu, 2012],

$$p_{XY}(x, y) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-\rho^2}} \exp^{-\frac{1}{2(1-\rho^2)} \left[\left(\frac{x-\mu_x}{\sigma_x}\right)^2 + \left(\frac{y-\mu_y}{\sigma_y}\right)^2 - \frac{2\rho(x-\mu_x)(y-\mu_y)}{\sigma_x\sigma_y} \right]}. \quad (2.22)$$

The normal density function p_{XY} is a hill-shaped surface whose peak occurs at the point $(x, y) = (\mu_x, \mu_y)$. The shape of the top view of the hill depends on the variance (σ_x^2, σ_y^2) of the two variables, and the correlation coefficient ρ ($|\rho| \leq 1$). The top view of the density distribution has elliptical shape whose major and minor axes are (σ_x^2, σ_y^2) . If $\rho=0$,

the ellipse axes are perpendicular meaning the two variables, X and Y , are statistically independent. If $|\rho|=1$, the ellipse collapses as a straight line. In such case, the JPDPF is singular thus $|\rho|$ is assumed to be always less than 1 [Duda et al., 2012].

Often, the probability of an outcome of a subset of the random variables in the joint density is of interest. Obtaining this probability is called marginalization, and it involves taking a weighted *sum*³ over the possible outcomes of the random variables that are of interest [Levy, 2012]. A marginal density function is described as,

$$P((X = x, Y = y) \in \mathcal{A}) = \int \int_{\mathcal{A}} p_{XY}(x, y) \, dx dy, \quad (2.23)$$

where $\mathcal{A}$ is the domain. Hilbert marginal spectrum $h(f)$ is a distribution of energy density at frequency f . This can be used to define the JPDPF $p(f, A)$ of the frequency f and amplitude A extracted from all IMFs [Schmitt et al., 2009]. The marginal Hilbert spectrum is then rewritten as,

$$h(f) = \int_0^\infty p(f, A) A^2 dA. \quad (2.24)$$

This definition corresponds to a second statistical moment and can be generalized to account for arbitrary orders of intermittency analysis as a more accurate substitute for structure functions [Huang et al., 1999, 2008a, 2014, 2008b].

$$\mathcal{L}_q(f) = \int_0^\infty p(f, A) A^q dA, \quad (2.25)$$

where $\mathcal{L}_q(f) \sim f^{-\zeta(q)}$, and $\zeta(q)$ is the scaling exponent obtained using the Hilbert spectral analysis. The Hilbert scaling exponent $\zeta(q)$ can be related to the scaling exponent obtained using structure functions $\xi(q)$ through the relation $\xi(q) = \zeta(q) - 1$ [Huang et al., 2010, 2011, 2013, Tan et al., 2014]. For $q = 2$, $\mathcal{L}_2(f)$ is the marginal Hilbert spectrum $h(f)$.

This relation allows the comparison between the scaling exponent obtained by structure function to the scaling exponent obtained by Hilbert spectral analysis, which can be used to compare the intermittency obtained by the two methods.

2.5 Magnitude Cumulants

Castaing [Castaing et al., 1990] described the turbulence cascade and ESS accounting to the deformation in the probability distribution function of velocity increments and time scales using the equation below [Castaing et al., 1990, 1993, Delour et al., 2001, Malécot et al., 2000],

$$P_\tau(\delta v) = \int_{-\infty}^{\infty} G_{\tau\tau'}(u) e^{-u} P_{\tau'}(e^{-u}\delta v) du, \quad (2.26)$$

where $G_{\tau'}$ is a propagator and τ' is an arbitrary time scale that is larger than τ . The velocity increments are decomposed as $\prod_{i=1}^n W_{\tau_{i+1},\tau'} \delta v_{\tau'}$ in which $W_{\tau_{i+1},\tau'}$ represents an independent variable of law $G_{\tau\tau'}$. The scaling exponent ξ_q and the scales function $f(\tau)$ in the ESS approach can be related through the shape of $G_{\tau\tau'}$ via the “magnitude” of the cumulant generating function $\log|\delta v_\tau|$ [Delour et al., 2001].

$$\log \widehat{G_{\tau\tau'}}(-iq) = \log(B(q,\tau)) / \log(B(q,\tau')) = \xi_q (f(\tau) - f(\tau')). \quad (2.27)$$

The estimation of structure functions for higher orders can be challenging when seeking statistical convergence. Delour et al. [2001] suggested an alternative approach in which the intermittency coefficient can be estimated without computing moments as high as the 6th order using the former relation between velocity increment and propagator $G_{\tau\tau'}$. In this approach, the magnitude cumulant analysis, the polynomial development

of $\log(B(q, \tau)) / \log(B(q, \tau'))$ versus q includes the cumulants $C_n(\tau) = -c_n f(\tau)$ of the generator $\log |\delta v_\tau|$, the cumulants are given by [Basu et al., 2007],

$$\langle |\delta v_\tau|^q \rangle = \exp \left(\sum_{n=1}^{+\infty} C_n(\tau) \frac{q^n}{n!} \right), \quad (2.28)$$

where the first, second, and third cumulants are described as,

$$C_1(\tau) = \langle \log |\delta v_\tau| \rangle \sim -c_1 \log(\tau), \quad (2.29)$$

$$C_2(\tau) = \langle \log |\delta v_\tau|^2 \rangle - \langle \log |\delta v_\tau| \rangle^2 \sim -c_2 \log(\tau), \quad (2.30)$$

$$C_3(\tau) = \langle \log |\delta v_\tau|^3 \rangle - 3 \langle \log |\delta v_\tau|^2 \rangle^2 \langle \log |\delta v_\tau| \rangle + 2 \langle \log |\delta v_\tau| \rangle^3 \sim -c_3 \log(\tau). \quad (2.31)$$

Typically, the 6th order structure function is used to obtain intermittency exponent $\mu = 2 - \xi_6$ for long-normal processes. Basu et al. [2007] states that a relation between the intermittency exponent μ and the second cumulant coefficient c_2 for a log - normal process can be arrived by relating velocity increments with dissipation rate and is described as;

$$\mu = 9c_2. \quad (2.32)$$

Thus, the intermittency exponent can be obtained without resorting to 6th moment statistics by employing the magnitude cumulant analysis.

For a Gaussian process, the asymptotic values of the three cumulants at large scales ($\tau \rightarrow T$) are $C_1(\tau) = -0.64$, $C_2(\tau) = \pi^2/8$, and $C_3(\tau) = -2.1$ where T is the integral time scale [Basu et al., 2007]. Previous studies also show that the third cumulant has a slope of zero [Basu et al., 2007, Chevillard et al., 2005].

Numerous studies have provided descriptions to the cascade of nonlinear data sets [Grahovac et al., 2018, Schmitt, 2003, Wendt et al., 2007]; and many using the magnitude cumulant analysis to estimate intermittency [Arneodo et al., 1999, Chevillard et al., 2005, Dertinger et al., 2009]. Kahalerras et al. [1998] and Malécot et al. [2000] investigated Reynolds number effects on scaling exponent as well as the relative cumulant. Other studies conducted wavelet base cascade cumulant analysis [Venugopal et al., 2006a,b]. The function $g = \log |\delta v_\tau|$ is the generator of the cumulant generating function $\Psi(q, \tau)$, which is given by $\Psi(q, \tau) = \log B(q, \tau)$. The theorem of Marcinkiewicz states that, if it exists, the development in equation 2.28 is either infinite, or if finite, of degree not higher than 2. In fact, its development may not exist in case of non-analyticity of $\Psi(q)$ [Michalec et al., 2015, Schmitt et al., 2009]. Thus, the cumulant generating function can be rewritten as,

$$\Psi(q) = C_1 q + C_\alpha q^\alpha, \quad (2.33)$$

where for a quasi-Gaussian process $0 \leq \alpha \leq 2$, and $\alpha = 2$ corresponds to a Gaussian process. The polynomial development of $\Psi(q)$ exists only when $\Psi(q)$ is a non-analytical function. For that reason, the cumulant C_α is called the non-analytical cumulant [Michalec et al., 2015]. Unlike the magnitude cumulant, non-analytical cumulant analysis yields one scaling exponent α for all time scales. The index α and the non-analytical cumulant can be computed from equation 2.33 as,

$$\phi(q) = \Psi(q) - C_1 q, \quad (2.34)$$

where $\phi(q) = C_\alpha q^\alpha$ and is a function of q^α . $\phi(q)$ is a second Laplacian function that is convex when plotted against q , using curve fitting of power law function for $(\phi(q))$ versus (q) yields the values of both α and C_α [Schmitt et al., 2009].

2.6 Control Volume Analysis

Control volume analysis is conducted by marking a box that encapsulates the flow within the region of interest. The box is then used to evaluate the net momentum and kinetic energy of the flow. The analysis has been used in previous studies to investigate mean and turbulent kinetic energy distribution in wind farms [Cortina et al., 2016], momentum transport in jets [Freedland et al., 2020], flux in heterogeneous surfaces [De Roo and Mauder, 2018], and convection in solar panels [Stanislawski et al., 2020]. The analysis provides a global description of the flow with the control volume (CV). Freedland et al. [2020] was able to compare different cases of jet speeds by integrating each over its own CV then obtaining momentum and kinetic energy per unit volume. It allows capturing features that might be located in different locations or occurring in different scales with respect to the object investigated depending on various parameters.

The control volume (CV) analysis of the momentum equation is presented herein. the steady state momentum equation is described as,

$$U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} - \frac{\partial \overline{u'_i u'_j}}{\partial x_j} + \nu \frac{\partial^2 U_i}{\partial x_j^2} + F_i; \quad (2.35)$$

$$\frac{\partial u_j}{\partial x_j} = 0, \quad (2.36)$$

where the term to the left hand side of the equation is the momentum advection, while the terms on the right hand side are pressure gradient term, Reynolds stress term, viscous term, and body force, respectively. Evaluating the net momentum within the CV entails integrating every term in the equation over that CV as;

$$\overbrace{\iiint_{\mathcal{V}} U_j \frac{\partial U_i}{\partial x_j} d\mathcal{V}}^{\hat{A}} = - \overbrace{\iiint_{\mathcal{V}} \frac{\partial \overline{u'_i u'_j}}{\partial x_j} d\mathcal{V}}^{\hat{F}} + \overbrace{\iiint_{\mathcal{V}} \left[\frac{-\partial P}{\rho \partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j^2} + F_i \right] d\mathcal{V}}^{\hat{R}}. \quad (2.37)$$

The volume integral of advection and Reynolds stress terms can be evaluated using surface integration by invoking the divergence theorem as follows,

$$\iiint_{\mathcal{V}} U_j \frac{\partial U_i}{\partial x_j} d\mathcal{V} = \iint_S U_i U_j \cdot n_i dS, \quad (2.38)$$

$$\iiint_{\mathcal{V}} \frac{\partial \overline{u'_i u'_j}}{\partial x_j} d\mathcal{V} = \iint_S \overline{u'_i u'_j} \cdot n_i dS. \quad (2.39)$$

In the previous equations, n_i is a unit vector in the x , y , or z direction that has a unity value in the direction normal to the integration surface and zero otherwise, the surfaces and unit vectors are shown in Figure 4.48. The term $\partial \overline{u'_i u'_j} / \partial x_j$ is manipulated into the form $\overline{u'_i u'_j}$ by using the following relationship;

$$\frac{\partial u'_i u'_j}{\partial x_j} = u'_i \frac{\partial u'_j}{\partial x_j} + u'_j \frac{\partial u'_i}{\partial x_j}, \quad (2.40)$$

where the first term on the right hand side represents the continuity equation and is equal to zero. The same procedure is applied to the advection term. After evaluating the surface integral over the six surfaces of the CV, the net value of each term is obtained by summing these six values as;

$$\begin{aligned}
 \iiint_V \hat{A} dV = & \iint_{S_1} (UU + UV + UW) dS_1 - \iint_{S_2} (UU + UV + UW) dS_2 \\
 & + \iint_{S_3} (UV + VV + VW) dS_3 - \iint_{S_4} (UV + VV + VW) dS_4 \\
 & - \iint_{S_5} (UW + VW + WW) dS_5 + \iint_{S_6} (UW + VW + WW) dS_6.
 \end{aligned} \quad (2.41)$$

$$\begin{aligned}
 \iiint_V \hat{F} dV = & \iint_{S_1} (\overline{u'u'} + \overline{u'v'} + \overline{u'w'}) dS_1 - \iint_{S_2} (\overline{u'u'} + \overline{u'v'} + \overline{u'w'}) dS_2 \\
 & + \iint_{S_3} (\overline{u'v'} + \overline{v'v'} + \overline{v'w'}) dS_3 - \iint_{S_4} (\overline{u'v'} + \overline{v'v'} + \overline{v'w'}) dS_4 \\
 & - \iint_{S_5} (\overline{u'w'} + \overline{v'w'} + \overline{w'w'}) dS_5 + \iint_{S_6} (\overline{u'w'} + \overline{v'w'} + \overline{w'w'}) dS_6.
 \end{aligned} \quad (2.42)$$

Chapter 3

Experimental Setup and Large Eddy Simulations

This chapter covers the experimental methods, experimental matrices, and simulation suits conducted to obtain all the sets of data employed in this study. The data is gathered to answer questions related to variable canopy arrangement and the turbulent transport of momentum and energy response to them.

3.1 Horizontal Axis Wind Turbine Array

The setup described here is for a conventional horizontal axis wind farm used to examine turbulence fluxes in the canopy vicinity. Experiments were carried out in a closed-return low speed wind tunnel at Portland State University (PSU). The test section is 5 m in length with a width of 1.2 m and a ceiling height of 0.8 m. The contraction ratio of the wind tunnel is 9:1 with operational velocities in the test section ranging 2 to 40 ms^{-1} . Free stream turbulence was generated with a passive grid and the flow in the test section was sheared using vertical strakes to produce the desired inflow profile. Roughness elements consisting of rows of chains were used on the floor of the test section to further condition the incoming flow. Wind turbines operate in ABL characterized with an effective roughness scale $y_o = 4.2 \text{ mm}$, effective friction velocity $u_* = 0.385 \text{ ms}^{-1}$, and a boundary layer velocity deficit $\Delta U^+ = 14.9 \text{ ms}^{-1}$ [18]. The streamwise turbulence intensity has an average value

of 13.5% in the interrogation area. For more details about boundary layer characterization, turbulence intensity profile, and streamwise velocity profile in linear and logarithmic scales, the reader is referred to [Hamilton et al., 2015].

A 3×4 array of model wind turbines of rotor diameter $D = 120$ mm and hub height $H = 120$ mm was installed in the test section. The data are collected behind the fourth turbine, for which the peak tip speed ratio is $\lambda = 3.5$, to ensure fully developed flow. By the fourth row, the wakes fields behind turbines do not vary significantly with the row number. The wind turbines were positioned with a streamwise spacing of $6D$ and a spanwise spacing of $3D$, which contains the recovered wake of the preceding turbine which has been shown to occur $6D$ downstream in previous studies [Ali et al., 2018]. The study [Ali et al., 2018] also showed that $3D$ spanwise spacing ensures developed wake in that direction as there was no variation in the wake flow between $1.5D$ and $3D$ spacing. The experimental setup is shown in Fig. 3.1. The ratio of wind tunnel Reynolds number to field Reynolds number is equal to the model turbines scale. Away from turbine blade, both the wind tunnel and the field Reynolds numbers are large suggesting that large scale turbulence characteristics converge on Reynolds number [Hamilton et al., 2012]. In [Chamorro et al., 2012] it was found that except in the near wake area, mean velocity and turbulence statistics in wind turbine wakes were Reynolds number independent. Hence, effects of Reynolds number on the observed statistics of large scale turbulence are neglected. Further details of the experimental setting and wind turbine models manufacturing and scaling are provided in [Hamilton and Cal, 2015, Hamilton et al., 2015].

Stereo particle image velocimetry (SPIV) was used to measure the velocity fields immediately upstream and downstream the center line turbine of the fourth row in the array. The inflow conditions on the fourth row turbine can be assumed to exhibit similar behavior

Figure 3.1: Diagram of the wind farm experimental setup as viewed from the side at PSU wind tunnel facility. The diagram is not to scale.

to the far wake of the same turbine [Chamorro and Porte-Agel, 2011].

The SPIV system supplied by LaVision consisted of a 532 nm wavelength double-pulsed Nd:Yag laser (1200 mJ pulse, 4 ns pulse duration) and two pairs of CCD cameras set up for simultaneous acquisition of both regions of interest (ROI). Neutrally buoyant tracer particles of diethylhexyl sebacate were injected into the test section to seed the flow field. The camera setup resulted in ROIs to be $230 \text{ mm} \times 230 \text{ mm}$. Calibration of the cameras was performed using a two-plane calibration plate. Data were collected at 1 Hz frequency and the maximum particle displacement was set to be 6 pixels for each measured plane. For each ROI, 2000 SPIV image pairs were collected providing a sample size comparable to other experiments in which conditional statistics were applied to vector fields [Nolan et al., 2010, Roussinova et al., 2009]. Vector fields were extracted from the image pairs using a multi-pass FFT-based correlation algorithm within the LaVision software with window size of 64×64 pixels. The resulting spatial resolution of the vector field was 1.5 mm and the uncertainty for second-order statistics was determined to be 3% using the method described by Sciacchitano et al. [Sciacchitano and Wieneke, 2016].

Figure 3.2: Side view schematic of PSU wind tunnel showing the wind turbine, laser sheet, and inflow conditions. The diagram is not to scale.

3.2 Vertical Axis Wind Turbine

This data set is acquired experimentally to examine the dynamics of a vertical axis wind turbine wake for its relevance in collocated wind farm arrangements proposed in this work. The experimental tests are conducted at the Portland State University wind tunnel, which is a return type with test section dimensions of length, height, and width of 5 m, 0.8 m, and 1.2 m, respectively. It has a 9:1 contraction ratio and a $2\text{--}40\text{ ms}^{-1}$ velocity range. The tunnel floor has small chains of average diameter 0.0075 m to represent roughness. Inflow turbulence is introduced by a passive grid constructed of 7 vertical and 5 horizontal rods made of steel at the tunnel entrance that also contain $(10\text{ cm} \times 10\text{ cm})$ strakes that provide the necessary shape to shear the flow. The turbine is placed 200 cm away from the entrance at the center of the tunnel width. Figure 3.2 shows a schematic of the experimental setup.

The wind turbine three-dimensionally printed model consists of a three bladed rotor of 45 mm diameter and 90 mm height. The rotor is fastened to a 6 mm diameter and 86 mm total height of motor and nacelle which makes the midspan height of the turbine 130 mm. Also, the model turbine has a tip speed ratio of 0.56. A sketch of the model wind

Figure 3.3: Dimensions and position of the wind turbine model and interrogation area as viewed by the cameras in front, top, and iso view. Units are mm.

turbine is illustrated in Figure 3.3.

Data are acquired using particle image velocimetry. A pair of CCD cameras are used to measure the velocity fields downstream of the turbine at midspan elevation and $1D$ away from the centerline, the center of the turbine is the origin of the coordinate system. The interrogation area as seen by the cameras is $230 \text{ mm} \times 230 \text{ mm}$. A 532 nm wavelength double-pulsed Nd:Yag laser with a 1200 mJ/pulse at duration of 4 ns generates the laser sheet. 2000 image pairs are collected at 4 Hz sampling frequency to ensure converged statistics and unbiased data set. This results an error of less than 1% and 3% for the first and second order statistics, respectively. The data gathered are passed through FFT-based correlation algorithm. The resulting spatial resolution of the vector field is 1.5 mm and the uncertainty in vector values is estimated to be 3% using two points correlation. Calibration

Figure 3.4: Schematic illustrating experimental setup at Oldenburg wind tunnel facility. The diagram is not to scale.

of the cameras was performed using a two-plane calibration plate.

3.3 Floating Wind Farm

As part of answering questions related to developing floating offshore wind farms, experimental tests are conducted to obtain the data needed for the analysis. The data is collected in two closed loop wind tunnels at the University of Oldenburg. The test section has a $0.8 \text{ m} \times 1 \text{ m}$ cross-sectional area and is 5 m long. The tunnel entrance is provided with winglets attached to 7 horizontal and 9 vertical shafts. The shafts are then connected to motors that can be set to run according to certain protocols to generate the desired turbulence intensity of the incoming flow. A schematic of the wind tunnel can be seen in Figure 3.4.

The turbine model consists of 0.2 m rotor diameter, 0.028 m diameter and 0.24 m long nacelle, and 0.016 m diameter motor [Rockel et al., 2017]. The data is collected using 1 mm length Dantec 55P16 hot wires that are operated using CTA 54N80 Dantec

Figure 3.5: Single wind turbine model and measurement locations (top). Hot-wires rake (bottom).

Figure 3.6: Two wind turbines setup and measurement locations. Measurements are taken at the hub height.

multichannel.

Two sets of experimental data have been used in the analysis: single floating and fixed wind turbine, and two floating and fixed wind turbines. The experimental setup of each data set is described below.

For the single floating wind turbine data set, single wind turbine model free to oscillate in streamwise direction with a pitch angle up to 15° is used. The oscillations are caused by the incoming wind. The turbine is placed 1.09 m from the entrance, and the data is collected at downstream locations up to $7D$. A total of 16 hot wires are placed on a rake to collect the data in 8 vertical, 4 horizontal, and 4 in 45° diagonal locations with 33 mm ($0.165D$) spacing between each two successive hot-wires, see figure 3.5. The turbine is subjected to two inflow conditions: passive grid case in which the grid is fixed and a low

turbulence intensity of 1.8% is produced, and active grid case in the grid is ran through variable speeds protocol and high turbulence intensity of 15.9% is generated. In order to check the active grid inflow condition reproducibility, measurements from all 16 hot-wires were recorded twice. Then, a cross correlation is calculated; amounting to 0.66 on average. Mean velocity deviations for passive and active grid inflow condition are less than 0.2% and 2.1%, respectively. For average turbulence intensity, the passive grid inflow condition had a 0.1% standard deviation, and the active grid case had a 0.5% standard deviation, which shows that the inflow conditions are reproducible. The same tests are performed on a fixed wind turbine for comparison. A detailed description of this data set can be found in [Rockel et al., 2017] and the experimental setup schematic is presented in Figure 3.5.

The second data set used in this study is for two floating wind turbines oscillating concurrently. The turbines are placed next to each other horizontally facing a passive grid inflow condition with a turbulence intensity of 4%. The measurements are collected 1D behind the two turbines at hub height using 11 one dimensional hot-wires at a sampling frequency of 20000 Hz. The hot-wires are spaced 7.5 cm ($0.375D$) in the spanwise direction except for the hot-wires in between the two turbines which are 5 cm ($0.25D$) apart. A top view of the setting is illustrated in Figure 3.6.

3.4 Forest Canopy

The experiments proposed herein are designed to study the effects of heterogeneous forest canopy distribution on the atmospheric boundary layer within and above the canopy. A heterogeneous forest canopy is represented as alternating patches of scaled model trees and gaps. Two different patch lengths and three different gaps are investigated as well as a homogeneous case with no gaps. The experiments are conducted in the Portland State

University wind tunnel facility, and the data are collected via Particle Image Velocimetry (PIV). Sections 3.4.1 and 3.4.2 present in detail the forest model and the experimental matrix.

3.4.1 Forest model description and scaling

The model unit proposed here is a patch of inter-connected trees. Interactions between neighboring trees, such as branch meshing between two trees or more, introduce additional effects which necessitate the careful design of canopy models. By including neighbor interactions, models of averaged forest patches provide a realistic representation of canopy dynamics at the cost of neglecting individual tree characteristics [Rodrigo et al., 2007].

The tree model represents a conifer tree with 200:1 scaling ratio. The model tree height $h_c = 10$ cm is divided equally into a 5cm trunk and a 5 cm crown. The crown is a conical shape with a 44° angle at the top and 4 cm diameter at the bottom. The tree trunk diameter is modeled according to the metabolic theory of ecology (MTE). The theory, introduced by West et al. [1999], employs the trees stable metabolic to obtain an invariant morphological scaling between several tree dimensions including trunk diameter, branch diameter, tree height, crown area, and crown volume. The MTE is used in this work because it is species and age independent [Antin et al., 2013]. For a model crown diameter of 4 cm, a model trunk diameter is estimated to be 2 mm.

The patches are constructed of reticulated foam with a porosity 10 PPI. Reticulated foams have been shown to accurately reproduce flows within forest canopies [Gromke and Ruck, 2018, Rodrigo et al., 2007]. The foam porosity can be translated into a leaf area index (LAI) which is a measure of leaf to gap ratio per unit area. In field data, the LAI is measured by taking images looking vertically at a tree crown from the ground, then using

various techniques, the ratio of crown area covered by leaves to that covered with gaps is measured. In this study, the LAI is obtained by taking images of the front view of a single tree placed in front of a white light source. The images are then processed to compute the ratio of black to white pixels. Black pixels represent areas covered with leaves, whereas white pixels represent the gaps. These ratio represent the leaf area density(LAD) at each vertical location. The LAI is then computed by integrating the LAD profile which is found to be 5.3 for the current tree model. Figure 3.7 shows the LAD profile of a single tree.

Figure 3.7: From left to right, this figure presents vertical profile of LAD of a single tree, an image taken for the front view of a tree with light source behind it, and the vertical segments over which the LAD is evaluated.

The canopy models are manufactured as patches. A sheet of reticulated foam with the desired dimensions of a single patch is soaked in oil, coconut oil is chosen for its low

solidifying temperature. The foam is then frozen to create a solid structure "mold" that can be machined. The mold is then machined with high speed CNC machine using a cutting bit that is 44° angled to obtain the desired tree crown profile. While machining the foam, the produced trees are kept connected at the bottom. The patch is then washed carefully to remove the excess oil, then placed on the tree trunks as shown in figure 3.8. Multiple patches are stacked together in order to create larger patches whenever needed.

Figure 3.8: Forest patch model.

3.4.2 Experimental matrix

The experimental matrix is designed to investigate the effects of forest heterogeneity in the streamwise direction. The forest model consists of successive forest patches and gaps. The patch length (L_p) and the gap length (L_g) are determined according to the flow development within each patch as well as over the entire forest. Lopes et al. [Lopes et al., 2015] showed that the flow is fully developed when the number of forest pattern (forest patch followed by a gap) is at least 4. The gap has an effect that is similar to a backward-facing step (BFS) and a forward-facing step (FFS) on the flow. In [Fontan et al., 2013], the gap size was investigated and three areas were identified. At downstream location greater than $x/h_c = 0.5$ the flow detaches, then the flow reattaches at $x/h_c = 2$. On this basis, the patch and gap lengths are chosen such that there are at least 4 patches upstream the measurement location and one after it can fit in the test section, while the three areas behind a BFS are

covered. The full matrix of proposed scenarios is presented in table 3.1 along the LAI, drag coefficient C_d , and the heterogeneity index Λ_g .

Table 3.1: Matrix of patch and gap dimensions in terms of the model canopy height, $h_c = 10 \text{ cm}$. The table also presents the drag coefficient C_d and the geometrical heterogeneity index Λ_g which will be discussed in later sections.

Case	Patch size L_p	Gap size L_g	L_g/L_p	C_d	L_c [m]	$\Lambda_g = \frac{L_c}{h_c}$	$\frac{U_\infty}{u_*}$	LAI
p_2g_1	$2h_c$	$1h_c$	0.5	0.98	0.13	1.3	16.87	
p_2g_2		$2h_c$	1	0.85	0.16	1.6	16.4	
p_2g_4		$4h_c$	2	0.54	0.2	2	15.8	
p_4g_4	$4h_c$	$4h_c$	1	0.8	0.3	3	15.5	
R_∞	$40h_c$	No Gap	0	NA	0.028	0.3	18	5.3

3.4.3 Measurement set 1: xz PIV planes

The experiments are conducted in a closed loop wind tunnel at Portland state University facility, the experimental setup is shown in Figure 3.9. Stereo particle image velocimetry (PIV) is used to take measurements in xz planes at five vertical locations, $y/h = 0.4, 0.75, 1.1, 1.25$, and 1.5 . The SPIV measurement window is $20 \text{ cm} \times 20 \text{ cm}$ which covers two canopy height in either direction. The planes extended over a full pattern P from the center of one patch to the center of a successive one. Exception to that, the location below the canopy height due to technical difficulty. Multiple successive PIV planes are collected when the pattern length is longer than $2h_c$.

Number of snapshots collected for each case is 2500 at a frequency of 3.75 Hz . First and second order statistics convergence is tested to ensure enough number of snapshots. For each measurement plane, the time difference between image pairs Δt is selected such that the maximum particle displacement in the measurement plane is 6 pixels. The data is

collected at five vertical location, every time the laser sheet was moved to a new location, the cameras were moved accordingly to ensure the same FOV area is covered by keeping distance between the cameras and the laser sheet constant. Collected images are processed using stereo cross correlation of 48×48 pixels interrogation area size with 50% overlap followed by two passes of 24×24 pixels interrogation area size. Erroneous vectors are removed using a median filter. Spurious vectors are replaced with vectors computed via interpolation from valid neighboring vectors. The uncertainty in the second order statistics was found to be 3% using the statistical correlation method implemented in DaVis version 4.8.0. based on [Wieneke, 2015].

Three canopy-height based Reynolds numbers are tested using inflow velocity of 5 ms^{-1} , 7.5 ms^{-1} , and 10 ms^{-1} with an open tunnel arrangement. Open tunnel arrangement allows the flow turbulence to be generated solely by the canopy. The forest models are placed at the tunnel entrance and extend all the way to the end of the test section to represent an infinite forest canopy. Thus, the measurements are taken in the canopy sub-layer.

3.4.4 Measurement set 2: xy PIV planes

The second set of measurements is collected for the same canopy arrangements in the experimental matrix, but the data is collected in an xy plane for vertical resolution. Two PIV windows are stacked on top of each other vertically and collected simultaneously covering a distance of 40 cm from the tunnel floor, which is equivalent to $4h_c$. The measurements are taken in the gap between two successive patches. For cases where the gap size is larger than the PIV window, two PIV planes are collected in the streamwise direction to cover the entire gap. Broader range of Reynolds numbers are collected in this set of measurements including inflow velocities of 1, 2, 5, 7.5, and 10 ms^{-1} .

Figure 3.9: Portland State University wind tunnel with model canopy patches and measurement planes to scale for $L_p = 2h_c$ and $L_g/L_p = 1$. Cameras trajectories are not to scale.

3.5 Collocated Wind Plant Simulations

The investigation of collocated wind plant layouts is carried out with the aid of a suit of numerical simulations. Simulations details and study cases are described in the following sections.

3.5.1 Large Eddy Simulations & wind turbine models

Large eddy simulations are conducted in this work to simulate the turbulent atmospheric boundary layer (ABL) flow in different wind farm configurations. The simulations conducted herein depict wind farms in neutrally stratified, pressure driven ABL flow where no thermal stratification effects are considered as well as no Coriolis effects. These generate a conical ABL, where the only elements of complexity are the wind turbine arrangements, and hence provide an opportunity to better understand the interaction between turbines and corresponding wakes. Therefore, continuity and Navier-Stokes equations are solved at each time-step for the resolved scales, and are described as,

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0, \quad (3.1)$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \left(\frac{\partial \tilde{u}_i}{\partial x_j} - \frac{\partial \tilde{u}_j}{\partial x_i} \right) = -\frac{\partial \tilde{P}^*}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \mathcal{F}_i^p + \mathcal{F}_i, \quad (3.2)$$

where the tilde ($\tilde{}$) indicates a filtered quantity. Here, u is the resolved velocity and subscripts i and j denote quantity components in the x , y , or z direction. A modified filtered pressure, $\tilde{P}^*$, given by $(\tilde{P}/\rho + \tau_{kk}/3 - \rho_\infty/\rho)$. The flow is driven by a constant pressure gradient, $\mathcal{F}^p$, and the effect of the turbines is indicated by their equivalent force on the flow through $\mathcal{F}_i$. The applied pressure gradient defines a reference, fixed friction velocity $u_\star$ by means of $u_\star = H\mathcal{F}_i^p$, H being the ABL height. This, in turn, is directly linked to an external geostrophic wind speed [Calaf et al., 2011]. The geostrophic velocity is given as;

$$u_g = \frac{u_\star}{k} \left[\ln \left(\frac{u_g}{f z_d} \right) - C_\star \right] = \frac{u_\star}{k} \left[\ln \left(Ro_h \frac{z_h}{z_d} \right) - C_\star \right], \quad (3.3)$$

where $C_\star$ is the empirical coefficient that has been determined to be $C_\star=4$ by previous studies [Calaf et al., 2011]. Ro_h and z_d are the Rossby number at the hub height and the effective roughness length, respectively. The effective roughness length results from the average flow behavior above the wind farm, thus it differs based on farm arrangement for given pressure gradient and friction velocity. The different roughness length lead to different $u_\star/u_g$ ratio, hence it is preferred to used the geostrophic velocity as an externally imposed parameter to scale wind speed when various wind farm arrangements are considered [Calaf et al., 2011].

Viscous forces are neglected due to the large Reynolds number flow [Calaf et al., 2010]. A scale-dependent Lagrangian dynamic model is employed to account for the effect of the sub grid scales (SGS) turbulence. For more details about the SGS model, the reader is

referred to [Bou-Zeid et al., 2005, Calaf et al., 2010]. In the numerical code, Zero momentum flux boundary condition is applied at the top of the domain, while a no-slip and impenetrable surface conditions are applied at the bottom. A log-law shear stress is enforced at the first grid point above the surface for the horizontal momentum components. A Pseudospectral approach is used to integrate the equations in the horizontal directions and second-order finite differences are used in the vertical direction. The equations are integrated in time using a second-order Adam-Bashforth scheme [Hezaveh et al., 2017].

Two types of wind turbines, VAWT and HAWT, are modeled in this study. The actuator line model (ALM) is used to simulate the VAWT blades as vertical lines. The turbine body force is obtained using the blades airfoil characteristics then integrated in the LES and tracked in time to compute the tip speed ratio and relative wind speed necessary to obtain the drag and lift coefficients, see [Hezaveh et al., 2017, 2018] for details. A distributed force method is used to limit the ALM sensitivity to the simulations domain grid size, given the small blade dimensions, by distributing the force equally over the chord length and over multiple cells. This LES code has been validated with experimental data in [Hezaveh et al., 2017]. In modeling the HAWTs, an actuator disk model (ADM) is used. The streamwise disk thrust force is computed as;

$$\mathcal{F}_i = \frac{1}{2} \rho C'_T \langle \bar{U}^T \rangle_d^2 \frac{\pi}{4} D^2, \quad (3.4)$$

where C'_T is $(C_T/(1-a)^2)$, with C_T and a being the thrust coefficient and induction factor, respectively [Burton et al., 2001]. The angular brackets $\langle \rangle_d$ indicate spacial averaging over the disk swept area, while the over bar $(-^T)$ denotes time averaging over a time scale T . The velocity $\langle \bar{U}^T \rangle_d$ is used instead of the often used free stream velocity U_∞ , given that this

quantity is not readily known in our simulations. Here we relate the free stream velocity to the disk velocity as $U_\infty = U_d/(1 - a)$ [Calaf et al., 2010]. The lower case d indicates that the averaging is over the disk area, while the upper case D is the disk diameter. Thrust and drag coefficients used in this study are 1.33 and 0.8, respectively [Ali et al., 2019, Calaf et al., 2010]. For detailed description of the numerical codes the reader is referred to [Calaf et al., 2010, Cortina et al., 2017a, Hezaveh et al., 2017].

3.5.2 Study cases & simulations domain

standard HAWT wind plant (SWP) arrangement is used as a base case to which two additional collocated wind plant arrangements are compared. The turbine spacing in the SWP array is $2.5D \times 7D$ in the spanwise and streamwise directions. Each HAWT is 80 m diameter and 80 m hub height. The collocated wind plant CWP cases are created by adding VAWTs to the SWP. The VAWTs are added as clusters of three turbines, illustrated in figure 3.10(c), due to the enhanced performance of the turbines when arranged in clusters compared to separately located turbines [Hezaveh et al., 2018]. A total of 12 clusters are added as 3×4 array in each collocated case. Note however, that since spectral methods are used to integrate the flow dynamics, the flow is in practice periodic. Hence, the modeled wind farm is infinitely large. This configuration is a good representation of the turbines located in the fully developed flow region in realistic wind farms. The added VAWTs are 10 m in diameter, and 10 m mid-rotor height, with a total height of 15 m. The clusters are positioned in alignment with the HAWT centerline to generate the aligned collocated configuration CWP_{al} . Whereas to generate the staggered collocated configuration CWP_{st} , the clusters were located midway between two HAWT in the spanwise direction. Schematics detailing the two collocated arrangements are presented in figure

3.10. The simulation domains extend $2400 \times 600 \times 640$ meters in the streamwise, span-wise, and vertical direction, respectively. The vertical dimension is equivalent to 8 rotor diameter to include the large atmospheric boundary layer (ABL) scales effect. The simulation domain as well as the wind plants dimensions are detailed in table 3.2.

Figure 3.10: Aligned (a) and staggered (b) collocated wind plant configurations illustrating the VAWTs locations with respect to the HAWT in each case. The standard plant arrangement is not shown as it has the same HAWTs layout as the collocated plants without the VAWTs. A zoomed-in schematic of a VAWTs cluster (c) illustrating the turbines dimensions and their location with respect to each other. Not to scale.

Table 3.2: Characteristics of the simulations domain and wind turbines specifications.

Domain variables	Value	Units
$L_x \times L_y \times L_z$	$2400 \times 600 \times 640$	[m]
$N_x \times N_y \times N_z$	$512 \times 192 \times 256$	grid points
$x_{box} \times y_{box} \times z_{box}$	$530 \times 120 \times 120$	[m]
$n_x \times n_y \times n_z$	$100 \times 50 \times 128$	grid points
HAWTs variables	Value	Units
Number	12 (3×4)	-
Spacing	$2.5D \times 7D$	Spanwise $\times$ Streamwise
z_{hub}	80	[m]
D	80	[m]
VAWTs variables	Value	Units
Number	36 (3 VAWTs $\times$ 12)	-
z_{bottom}	5	[m]
z_{top}	15	[m]
d	10	[m]

Chapter 4

Results

4.1 Quadrant Analysis ¹

Measurement of the horizontal wind turbine array described in section 3.1 are employed in this analysis. The $\overline{u'v'}$ Reynolds shear stress component provides a basis by which the other stresses are observed due to its role in the transport of momentum down into the turbine canopy from the free stream. Hence, it must be examined before applying conditional sampling to have an understanding of how it is influencing the momentum transfer.

4.1.1 Reynolds shear stresses

The total Reynolds shear stress contours for $\overline{u'v'}$ is shown in Figure 4.1. The axes are normalized by the turbine diameter $D = 0.12$ m with the wind turbine located at a stream-wise position of $x/D = 0$. The inflow plot represents the far wake of the third turbine, where the Reynolds shear stresses are accumulated as a consequence of prior turbines. The area above the nacelle is dominated by negative Reynolds shear stress, whereas below the nacelle has a diminutive positive stress. The inflow field does not seem to show any

¹The following results are adopted from, Kadum, H. F., Knowles, D., Cal, R. B. (2019). Quantification of preferential contribution of Reynolds shear stresses and flux of mean kinetic energy via conditional sampling in a wind turbine array. *Journal of Fluids Engineering*, 141(2)

noticeable change with downstream direction. In the wake, $\overline{u'v'}$ signs are conserved from inflow to wake as the flow passes through the turbine. This distribution is due to the vertical velocity component direction associated with the shear layer created by the rotor. Aforementioned regions are also stress maxima regions associated to mixing occurring with higher speeds due to the effect of shedding at the top and bottom tips. The stress magnitudes are increased by ≈ 1.5 times the inflow reaching maximum values of positive and negative Reynolds shear stress of about $-0.25 \text{ m}^2\text{s}^{-2}$ and $0.2 \text{ m}^2\text{s}^{-2}$, respectively, with the first more present causing a downward streamwise momentum flux dominance.

Figure 4.1: Total $\overline{u'v'}$ Reynolds shear stresses. Units are m^2s^{-2} . The horizontal lines refer to bottom tip, hub height, and top tip location.

Quadrant analysis as applied to the Reynolds shear stresses, $\overline{u'v'}$, $\overline{u'w'}$, and $\overline{v'w'}$ are shown in Figures. 4.2 - 4.4. The inflow stress fractions for $\overline{u'v'}$ are shown in Figure 4.2(a). It should be noted that the second and fourth quadrants of $\overline{u'v'}$ are multiplied by a minus sign for consistency amongst the quadrant and ease of comparison. A minus sign is included in the title above the contours to indicate their downwards directionality. The sweep and ejection events, Q_2 and Q_4 , have peak magnitudes approximately twice the magnitude of the peak interaction stresses, that is 0.137 vs. $0.063 \text{ m}^2\text{s}^{-2}$. The regions of peak inten-

sity for the sweep and ejection events are primarily located from the nacelle up into the free stream throughout the plane transferring momentum into the flow. This is consistent with the general trend that sweep and ejection events are prominent in high shear regions of boundary layer flows. The interaction events, Q_1 and Q_3 , show highest stress intensities in the plane region bounded by the top and bottom rotor tip. The inward interaction is slightly more localized, with the region of stress magnitudes of approximately $0.06 \text{ m}^2\text{s}^{-2}$ bounded by the nacelle and bottom rotor tip.

Figure 4.2: Stress fractions for $\overline{u'v'}$. Units are m^2s^{-2} . (a) Inflow and (b) Wake flow. Q_1 is the top right contour, Q_2 is the top left contour, Q_3 is the bottom left contour, and Q_4 is the bottom right contour.

The wake $\overline{u'v'}$ Reynolds shear stress fractions are shown in Figure 4.2(b). Similar trends to the inflow conditions are present with interaction events showing peak intensities in the region from the nacelle to the bottom rotor tip, and the sweep and ejection events showing intense regions at the high shear layers around the top tip. Peak sweep and ejection events show magnitudes of stress approximately 70% higher than that of the interaction events (0.2 compared to $0.13 \text{ m}^2\text{s}^{-2}$, respectively). Interestingly, interactions are bounded

in the region from the nacelle to the lower rotor tip in this near wake region, while looking to the inflow, or far wake, in Figure 4.2(a), the region of elevated interaction stresses has diffused to occupy the entire wake region. The interaction events occur deep in the canopy and without as much of an influence from the free stream. These regions of elevated stress are primarily caused by the motion of the rotor and the presence of the turbine mast. The persistence of the Reynolds stress and its events six diameters downstream indicates structural loads affecting the wind turbines as well as providing an indication for turbine placement [Thomsen and Sørensen, 1999].

The $\overline{u'w'}$ RSS conditionally sampled by $\overline{u'v'}$ is shown for the inflow and wake in Fig 4.3. Quadrants 2 and 3 in the inflow, Fig 4.3(a), show a homogenous stress signature throughout the plane at essentially negligible magnitudes of $0.016 \text{ m}^2\text{s}^{-2}$ or less. Elevated stress values are observed in quadrants 1 and 4 with peak stress magnitudes of approximately $0.036 \text{ m}^2\text{s}^{-2}$ distributed in the wake of the rotor. Stress peaks existence in quadrants 1 and 4 rather than quadrants 2 and 3 indicates the stress sensitivity to the sign of u component of velocity fluctuation. The relevance of $\overline{u'w'}$ Reynolds shear stress in the inflow/far wake is not associated with the dominance of sweep and ejection events. However, positive advection of momentum is coincident with maximum and positive $\overline{u'w'}$.

The $\langle uw \rangle$ Reynolds shear stress in the near wake region, Figure 4.3(b), acts similar to $\overline{u'v'}$ flow events. Sweep and ejection events, Q_2 and Q_4 , show a strongly negative stress signature in line with the top rotor tip. The mean stress levels in this region peak around $-0.08 \text{ m}^2\text{s}^{-2}$, with elevated stress magnitudes favoring sweep events. These stresses occupy the same region in the plane as the dominant $\overline{u'v'}$ stresses for sweep and ejection events, suggesting that negative $\langle uw \rangle$ stress is associated with a downward transfer of momentum. The interaction events, Q_1 and Q_3 , of $\langle uw \rangle$ both show weak positive stress, about 0.025

m^2s^{-2} , in the region from the nacelle to the top rotor tip. Interestingly, these positive stresses, though less pronounced, also occur in the same region in the sweep and ejection quadrants. The aforementioned feature is in contrast with the behavior of $\langle uw \rangle$ in the inflow since the wake experiences a streamwise velocity deficit and reduced advection of momentum in that direction. This quantity lends itself for modeling the out-of-plane RSS containing the effects due to rotation [Camp et al., 2016, Katul et al., 1997].

Figure 4.3: Stress fractions for $\overline{u'w'}$. conditionally sampled by $\overline{u'v'}$. Units are m^2s^{-2} . (a) Inflow (b) Wake. Quadrants as in Figure 4.2.

The $\overline{v'w'}$ RSS fractions conditioned on $\overline{u'v'}$ are shown in Figure 4.4 for inflow and wake. The inflow/far-wake region, Figure 4.4(a), shows essentially negligible mean stress levels well diffused in the plane for all quadrants. Of a note, the downward momentum quadrants, Q_2 and Q_4 , are dominated by negative $\overline{v'w'}$ and the upward momentum quadrants, Q_1 and Q_3 , are dominated by positive $\overline{v'w'}$. Hence, it can be inferred that the direction of $\overline{v'w'}$ is influenced by the direction of $\overline{u'v'}$ RSS component. Observing the near-wake region Figure 4.4(b), the largest stress magnitudes $0.06 \text{ m}^2\text{s}^{-2}$ occupy the plane region in line with the top rotor tip and are associated with sweep and ejection events.

These stresses are attributed largely to the motion of the turbine blades due to the lack of the bulk component of velocity. The $\overline{v'w'}$ RSS shows negligible persistence downstream, suggesting a larger dependence on the streamwise advection of the flow.

Figure 4.4: Stress fractions for $\overline{v'w'}$, conditionally sampled by $\overline{u'v'}$. Units are m^2s^{-2} . (a) Inflow (b) Wake. Quadrants as in Figure 4.2.

4.1.2 Relative comparison of sweeps and ejections: $\Delta S_{u_i u_j}$

Figure 4.5 shows the contour plots of the parameter $\Delta S_{u_i u_j}$ for $\overline{u'v'}$, $\overline{u'w'}$, and $\overline{v'w'}$ respectively. This parameter gives the prominence of sweep and ejection events according to the difference between their magnitudes. Positive values of $\Delta S_{u_i u_j}$ indicate that ejection is the dominant event, and negative values mean that sweep events are the primary contributors as both $S_{u_i u_j,4}$ and $S_{u_i u_j,2}$ are of negative values.

Figure 4.5(a) represents ΔS_{uv} for the incoming and wake flow. The inflow shows a sweep signature throughout the plane, and the region where sweeps are most dominant is located between hub height and top tip, $\Delta S_{uv} \approx -0.1$. For the wake flow, ΔS_{uv} continues to have its peak at the same location as the incoming flow, between hub height and

top tip. Comparing to Figure 4.1, the sweep dominance regions are exactly the maximum negative total $\overline{u'v'}$ RSS regions. Higher downwards streamwise RSS result from sweep events, while lower downwards streamwise RSS result from ejection events. Maximum sweep event in the near wake is 70% higher than its value in the far wake meaning sweep dominance is associated with momentum deficit accruing in the near wake. Sweep events are still present throughout the swept area, but the difference between the two events is not as significant below the turbine hub height where ΔS_{uv} ranges around -0.01. The convergence between ejection and sweep events occurrence is due to the increase in ejection events, which is caused by the interaction of the flow with bottom tip. The flow interaction with the bottom tip drives the flow upwards favoring positive v fluctuations which contributes to ejection in turn. Even though the wake has a sweep nature in general, ejections slightly overshadow sweep events near the shear layer after $x/D = 1.2$ as the flow starts recovering and consequently compensating the streamwise momentum shortfall.

ΔS_{uv} provides a map for which the distribution of sweep/ejection dominance is observed; the effect of this distribution on the other components of Reynolds shear stresses is at hand. The contour plots of ΔS_{uw} are shown in Figure 4.5(b). The inflow shows that the sweep dominance region (around the top tip) is associated with reduced positive $\overline{u'w'}$, whereas the region in which ejection events slightly overshadow the sweeps (below the hub height) is where $\overline{u'w'}$ maxima of 0.08 occurs. This behavior supports the finding that the inflow $\overline{u'w'}$ is more influenced by the streamwise advection of the flow, especially noting that the distribution of $\overline{u'w'}$ is persistent downstream. On the other hand, ΔS_{uw} highlighting the wake displays negative $\overline{u'w'}$ signature over the interrogation area signifying a sign switch between inflow and wake. The sign switch promotes the role of the direction of rotation of W component of velocity after interacting with the rotor. Furthermore, the

(a)

(b)

(c)

Figure 4.5: $\Delta S_{u_i u_j} = S_{u_i u_j,4} - S_{u_i u_j,2}$. The inflow to the left and the wake to the right.
 (a) ΔS_{uv} (b) ΔS_{uw} (c) ΔS_{vw} .

wake ΔS_{uw} plot reveals the influence of sweep and ejection events on $\overline{u'w'}$ as its peaks of -0.08 are coincident with both ejection and sweep dominance regions around and above

the hub height, and around the bottom tip, respectively. The location of dominance for sweeps highlights the ability of energy extraction and increased power production of the farm [Hamilton et al., 2012, Viestenz and Cal, 2016].

Figure 4.5(c) shows the plots of ΔS_{vw} . Sweep events promote positive $\overline{v'w'}$, and the region marginally favoring ejection events (below hub height) shows mixed negative and positive peaks of $\overline{v'w'}$. The ΔS_{uv} distribution leads the directional preference of $\overline{v'w'}$ in the inflow. In contrast, the wake ΔS_{uv} distribution has no effect on $\overline{v'w'}$ sign or magnitude. The wake plot of ΔS_{vw} communicates maximum $\overline{v'w'}$ within the momentum deficit region, yet no significant effect of sweep/ejection dominance distribution is observed. This behavior supports the balance between fluctuations, meaning as the other components of Reynolds shear stress, $\overline{u'v'}$ and $\overline{u'w'}$, have their intensities concentrated in the sweep and ejection dominance regions around the top tip and bottom tip for the wake flow, the $\overline{v'w'}$ component is prominence at the hub height.

All in all, sweep events are the primary contributor to downward momentum transfer and $\overline{u'v'}$ has the largest share in this contribution compared to $\overline{u'w'}$ and $\overline{v'w'}$. The sweep and ejection distribution of ΔS_{uv} has its significant influence on the intensity and directional preference of the remaining Reynolds shear stress components, however, it is not the only factor. The aforementioned parameters are subjected to the streamwise advection of flow momentum as well as the balance between velocity fluctuations. As the inflow sweep events are associated with elevated magnitudes of $\overline{u'v'}$ and $\overline{v'w'}$, the same does not apply to $\overline{u'w'}$ that yields more to the downstream transport of momentum and to the ejection events despite their modest superiority over sweep events. A similar trend presents itself in wake flow of $\overline{v'w'}$ Reynolds shear stress as it exhibits minimal dependance on ΔS_{uv} .

4.1.3 Exuberance

The exuberance computed by conditionally sampling $\overline{u'v'}$ is shown in Figure 4.6. Exuberance is the ratio between the events that contribute into upward flow to the events that contribute to downward flow. Values of exuberance with a magnitude less than -1 indicate interaction events dominance, while magnitudes larger than -1 indicate stronger influence from sweeps and ejections.

The incoming flow is generally influenced by sweep and ejection events except for the region between hub height and bottom tip, where interaction events dominate. However, the values of exuberance where interaction events dominate are not very intense, and are confined to the range -1 to -1.5 contributing a minimum to upward momentum transfer. The wake flow has the same trend as the inflow. Yet, the change in the exuberance values is significant. The wake flow experiences profound upward momentum movement behind the nacelle, where the interaction events are 3.5 times its inflow value. Below the bottom tip, the exuberance is about -1 or little less indicating that neither the upwards nor the downward events are dominant. The null momentum transfer is caused by the shear layer exists below the bottom tip, and its effect lessens after $x/D = 1.2$. Thereafter in the streamwise direction, the exuberance elevates above -1 showing the presence of downward momentum flux. A more pronounced downward momentum flux is associated with the other shear layer above the top tip and all the way down to the hub height, and it continues from very near wake all the way downstream.

4.1.4 Kinetic energy flux

For large wind turbine arrays, the vertical flux of kinetic energy is a primary mechanism by which the turbines are supplied with energy [Cal et al., 2010]. Sweep and ejection events

Figure 4.6: Exuberance, $E_{uv} = (S_1 + S_3)/(S_2 + S_4)$. Momentum transfer is primarily upward for values of $E < -1$ and conversely momentum transfer is directed downward for $E > -1$.

are the cause for downward kinetic energy flux, while the interaction events contribute to upward kinetic energy flux. The net contribution for each event across the swept area of a wind turbine is the difference between the flux at its bottom tip and the flux at its top tip.

Figures. 4.7 (a) and (b) represent the incoming and wake flow kinetic energy flux (KEF) contours, respectively. In the inflow, the interaction events have a local $\overline{u'v'U}$ distributed symmetrically throughout the field of view. The even distribution results in marginal upward net kinetic energy flux across the swept area, which is the difference between the top and bottom tip value of $\overline{u'v'U}$. This behavior is not present in the sweep and ejection events where $\overline{u'v'U}$ increases vertically. At the hub height, $\overline{u'v'U}$ magnitude increases rapidly towards the top tip reaching a maxima of $0.5 \text{ m}^3\text{s}^{-3}$ resulting in downward energy flux.

In the wake, the interaction events exhibit a different behavior than in the inflow. Although there is no significant change in $\overline{u'v'U}$ values between the top tip and the hub height, there is an evident change across the region from the hub height down below the bottom tip. The interaction events peak is shifting up in both magnitude and vertical position when moving downstream. The local values of $\overline{u'v'U}$ are about zero at the near wake

Figure 4.7: Conditionally averaged flux $F_k = -\langle uv \rangle_k U$ for (a) Incoming flow (b) Wake flow

at hub height due to flow blockage caused by the rotor. As the flow moves forward, it recovers its KE gradually allowing $\overline{u'v'}U$ to move gradually into this region. The sweep and ejection events show a similar trend as for having minor $\overline{u'v'}U$ near wake at hub height. The KE deficit recovers downstream, hence the downward KEF peak shifts towards the center of the turbine gradually. However, the increase of $\overline{u'v'}U$ magnitude is rapid and reaches a maximum value of $0.55 \text{ m}^3 \text{ s}^{-3}$.

For a more quantitative examination of the kinetic energy flux, the integrated value of the total as well as the conditional sampled $\overline{u'v'}U$ over the entire swept area are calculated as follows,

$$F_{net} = \int_{-D/2}^{D/2} \int_0^{1.6D} -\overline{u'v'}_k U \, dx dy, \quad (4.1)$$

where $D/2$ is measured from the hub height in the vertical direction, and $1.6D$ is measured immediately behind the turbine in streamwise direction.

The integrated value of total kinetic energy flux is $19.95 \text{ m}^5\text{s}^{-3}$. Net kinetic energy flux (KEF) of the wake quadrants shows that the ejection events contribute 45% of the net downward KEF, and the sweep events contribute 55%. The obtained values of net KEF for sweep and ejection are $28.8 \text{ m}^5\text{s}^{-3}$ and $23.4 \text{ m}^5\text{s}^{-3}$, respectively. Even though the sweep events are the prime contributor to downward KEF, the contribution of the ejection events is comparable. The net KEF of outward and inward interactions are $-16.3 \text{ m}^5\text{s}^{-3}$ and $-15.8 \text{ m}^5\text{s}^{-3}$, respectively. The total integrated KEF is $52.2 \text{ m}^5\text{s}^{-3}$ downward and $-32.1 \text{ m}^5\text{s}^{-3}$ upward, meaning 60% of the vertical transport of mean kinetic energy due to turbulence is directed downwards.

4.1.5 Summary

Conditional sampling of second-order products of velocity was performed on SPIV data collected in front of and behind the centerline of a turbine located in the fourth row of a 4×3 model wind turbine array. Aiming at assessing the effects of each event and the directional preference of momentum transfer on wake remediation and vertical entrainment for their implications on wind farm design.

Total $\overline{u'v'}$ Reynolds shear stress is found to entrain momentum into the wake via downwards transfer from above and via upwards transfer from below the bottom tip in the near wake. After two rotor diameters, the entrainment occurs by downwards transfer from the flow above the turbine. The conditionally sampled $\overline{u'v'}$ shows the downwards momentum transfer occurs by both sweep and ejection events. The sweep and ejection events still contribute to momentum transfer in the far wake.

The influence of $\overline{u'v'}$ Reynolds shear stress events on the $\overline{u'w'}$ and $\overline{v'w'}$ Reynolds shear stress component is investigated by looking at the behavior of these stress components

within the four quadrants of $\overline{u'v'}$ Reynolds shear stress. It is found that the sweep and ejection events of $\overline{u'v'}$ are associated with negative $\overline{u'w'}$ stress in the near wake. That means not only the $\overline{u'v'}$ is entraining momentum via sweep and ejection events, but also these events influence the $\overline{u'w'}$ component to be a contributor to wake recovery as well. This dynamic between the two stress components is not existent in the far wake. The scenario is reversed for $\overline{v'w'}$ Reynolds shear stress.

The relative comparison parameter ΔS_{uv} shows the main contributor to the downwards momentum transfer via $\overline{u'v'}$ Reynolds shear stress are the sweep events both in the near and far wake. This results is supported by the integrated flux being 55% generated by the sweep events, while the ejections contribute 45%. Both sweep and ejection events lead to negative $\overline{u'w'}$ Reynolds shear stress and no preference is observed. That means in the near wake any downwards $\overline{u'v'}$ event is associated with negative $\overline{u'w'}$ stress with no regards to whether the event is sweep or ejection. The same is true with $\overline{v'w'}$ Reynolds shear stress component. The Exuberance results shows that both near and far wakes are experiencing downwards momentum transport except for the region behind the hub.

4.2 Scaling and Development of Vertical Axis Wind Turbine Wake ²

The PIV data collected in the wake of a VAWT, see section 3.2 for experimental description, is used in this analysis. The mean velocity and Reynolds stress are plotted as a function of the spanwise and streamwise directions where the spatial coordinates are normalized by the rotor diameter D . Contours are presented for an overall assessment, concurrently, profiles at several downstream locations are illustrated to uncover further features

²The following results are adopted from, Kadum, H., Friedman, S., Camp, E. H., Cal, R. B. (2018). Development and scaling of a vertical axis wind turbine wake. Journal of Wind Engineering and Industrial Aerodynamics, 174, 303-311

of the VAWT wake. The profiles are plotted against z/D . The center of the turbine is the origin of the coordinate system. Thereafter, both the mean velocity and Reynolds stresses are scaled using various quantities with the aim of observing a possible collapse.

4.2.1 Wake development

The mean velocity components in all pertained directions are plotted as contours and profiles in Figure 4.8. Development of the wake downstream of the turbine is shown. The streamwise mean velocity, U , is presented in Figure 4.8(a). A maximum velocity deficit of 2.5 ms^{-1} is located at $x/D = 1$ around mid-span height. The wake begins to recover as the downstream distance is increased; even after $4.5D$, the wake is skewed towards the positive z -axis. This is a feature of VAWTs, where the passage of the turbines blades causes an imbalance in momentum in the direction of its rotation. The asymmetry of the wake is evident in Figure 4.8(d), where the peaks of the velocity profiles shift towards the positive z axis along the x direction. Profiles are also closer to each other after $x/D = 2.5$, signifying a decreased wake expansion after this particular location and dividing the wake into two regions. The regions are distinguished as $x/D \geq 2.5$ and $x/D \leq 2.5$. The reason behind the formation of these two regions is the effect of the rotor rotation that plays a significant role immediately after the turbine and starts to vanish gradually after $x/D = 2.5$, indeed after the remediating of the wake.

Figure 4.8(b) represents the vertical mean velocity component, V . Downward velocities are present at $z/D \leq -0.7$. On the other hand, the vertical mean velocity V is dominated by a positive sign at $z/D \geq -0.4$ since the direction of the rotation causes the rotor to push the momentum out of the wake in this part of the swept area. Similar to streamwise velocity, the vertical mean velocity has two distinguishable regions downstream. These two

Figure 4.8: Contours and downstream profiles of mean velocity and Reynolds stress components. Black curve separates the regions before and after $x/D = 2.5$. Units are ms^{-1} and m^2s^{-2} for velocity and Reynolds stress, respectively.

regions can be identified in Figure 4.8(e). Curves corresponding to the region after $x/D = 2.5$ display reduced variation as a function of transverse distance containing no significant change in values of V between $z/D = -0.54$ to $z/D = 1.5$. Its counterpart, curves corresponding to the region before $x/D = 2.5$, have three apparent peaks the maximum of which occurs at $z/D = 0.2$.

The spanwise mean velocity field, denoted by W , is shown in Figure 4.8(c). This component of the mean velocity explicitly states the influence due to the rotation of the turbine. The wake is skewed in the direction of the rotation. The velocity field is once again divided into positive and negative parts about the center of the rotor. The dominant portion is in the positive z direction which includes two peaks of magnitudes values around 0.9 ms^{-1} and 0.8 ms^{-1} , whereas the maximum value of the negative part is approximately -0.4 ms^{-1} . The two downstream regions are present once again in the spanwise velocity field, and curves in the region $x/D \geq 2.5$ tend to show a reduced variation as the flow advects downstream thus remaining in proximity to each other. These profiles are again relatively more homogeneous with respect to the transverse direction. This feature is present beginning at $z/D = 1$ into the positive z direction, suggesting a decreased wake expansion in this region as shown in Figure 4.8(f).

Three components of the Reynolds stress downstream of the wind turbine are also illustrated in Figure 4.8. The $\overline{u'u'}$ component of Reynolds stress is plotted as a function of streamwise and spanwise location as presented in Figure 4.8(g). The wake is highly asymmetric as it has shifted towards the positive z direction; two peaks are present at the boundaries of the swept area. These intense stress regions specifically occur between $z/D = 0$ to $z/D = -0.5$ and $z/D = 1$ to $z/D = 1.5$, with the first being weaker and its attributes are more diffused. The features as induced by the turbine persist past $x/D = 4$.

$\overline{u'u'}$ Reynolds stress profiles downstream are shown in Figure 4.8(j). Curves at $x/D \geq 2.5$ exhibit a reduced expansion. The peak in the thicker and thinner part of the wake have a highest stress values of $3.7 \text{ m}^2\text{s}^{-2}$ and $4.6 \text{ m}^2\text{s}^{-2}$, respectively. The $-\overline{u'v'}$ component of the Reynolds stresses is illustrated in Figure 4.8(h). The $-\overline{u'v'}$ stress is mainly positive, especially near the positive shear layers with a peak value of $0.3 \text{ m}^2\text{s}^{-2}$. Negative $-\overline{u'v'}$ stress areas can be observed around the centerline of the rotor prior to $x/D = 2.5$. Pertinent to the profiles in Figure 4.8(k), the two regions are significantly distinguished due to the drop in the stress values. The profiles diverge from each other due to a sudden change in the wake behavior after $x/D = 3$, where the Reynolds stress values elevate to about 3 times.

The $\overline{u'w'}$ Reynolds stress is shown in Figure 4.8(i). The stress field is divided into a positive region and a negative region in the thicker and thinner parts of the wake, respectively and both are skewed towards the positive z axis. Of note, the $\overline{u'w'}$ component is the highest among the Reynolds shear stresses due to the effect of rotation because of an increase in the W component of velocity. The maximum stress intensities are located at $z/D = -0.4$ of $1.2 \text{ m}^2\text{s}^{-2}$ and at $z/D = 1.25$ of $1.2 \text{ m}^2\text{s}^{-2}$, respectively. $\overline{u'w'}$ Reynolds stress profiles, presented in Figure 4.8(l), show the difference between the wake behavior within the two regions; the second region has more flattened peaks and a reduced wake expansion identified by noting that the profiles are closer to each other in the second region than in the first.

4.2.2 Wake scaling

Results of scaling the mean velocity deficit profiles nondimensionalized by U_o , the minimum mean streamwise velocity per downstream location are [resented in Figure 4.9. The

Figure 4.9: Streamwise velocity deficit (a) Scaled by z/δ_i^* (b) Scaled by $(z - z_o)/\delta_i^*$.

spanwise coordinate is nondimensionalized as z/δ_i^* in subfigure (a) and $(z - z_o)/\delta_i^*$ in subfigure (b) where i is either (+) for the displacement thickness to the positive spanwise direction or (−) for the displacement thickness to the negative spanwise direction. Figure 4.9(a) shows that nondimensionalizing the spanwise coordinate by displacement thickness, z/δ_i^* , brings the velocity deficit profiles of the asymmetric wake closer to each other than the spanwise coordinate normalized by the rotor diameter D , see Figure 4.8(b). Half of the wake in the negative z direction, representing the thicker part of the wake, collapses. However, the counterpart of the profiles does not collapse, showing a dependence on the downstream position. This effect is a reflection of the shift of the wake as observed in Figure 4.8.

Figure 4.9(b) illustrates the normalized spanwise coordinate $(z - z_o)/\delta_i^*$, which contains the transverse shift in reference to the center of the wake per downstream profile. This normalized coordinate is adapted from [Thomas and Liu, 2004] for an asymmetric wake behind a plate. The Figure shows the success of this scaling collapsing both sides of

Figure 4.10: Normalized maximum velocity deficit spanwise location, z_o/D , with respect to rotor's center line at different downstream locations, x/D .

the profiles. Again, z_o effectively compensates for the effect of a skewed wake. Having an asymmetric wake causes the velocity profiles to experience changes not only with respect to x -axis, but also with respect to the transverse direction as a function of the momentum imbalance due to the rotation of the turbine. Adding the parameter z_o counteracts the additional change, proving to be key step in collapsing mean velocity deficit profiles. Contrarily, using $(z - z_o)/\delta_i^*$ is not sufficient to collapse the Reynolds stress profiles when they are normalized by U_o^2 . Hence, it is necessary to implement a more appropriate velocity scale in addition to normalizing the spanwise coordinate by the averaged displacement thickness, δ_o^* , as it was found herein to better scale the Reynolds stresses.

Aiming to reach an improvement in scaling the Reynolds stress profiles, three scalings are investigated and compared, where the Reynolds stresses are normalized by U_∞^2 , $U_\infty^2(d\delta^*/dx)$, and the turbulence kinetic energy (TKE) scalar value, k . The effect of each normalizing scale on the wake is discussed in regards to the differences in the normal and shear Reynolds stresses response to each scaling. Furthermore, a comparison between the effect of the three scalings on a particular Reynolds stress is highlighted to determine the collapse of the Reynolds stresses in this asymmetric wake, and thereafter connecting the stress response to the parameters within the specific scaling.

Figure 4.11 shows the normal and shear Reynolds stress components scaled by U_∞^2 . Profiles of $\overline{u'u'}$ component of Reynolds stresses are slightly closer to each other, but do not show a significant response to this normalizing quantity. The thinner part of the wake is more influenced by U_∞^2 than the thicker part, particularly at $x/D > 2$. For the shown Reynolds stresses, the profiles prior to $x/D = 2.5$ show less aptitude to scale than the profiles after that location. Furthermore, the profiles starting $x/D = 2.5$ collapse showing consistency with the wake velocity and Reynolds stress contours in having two distinguished regions. Looking at the $\overline{u'w'}$ component of Reynolds stress, profiles seem to collapse except for the very near wake thus showing a slightly improved scaling behavior than the rest of the components. $-\overline{u'v'}$ profiles collapse away from the centerline, where the variation in the wake peak between the two region observed in $\overline{u'u'}$ profiles is present. The $\overline{w'w'}$ component is evidently dependent on downstream location due to the rotation effect of the turbine, especially prior to $x/D = 2.5$, where the variation between the profiles is the largest among the Reynolds stress components.

In using $U_\infty^2 d\delta_o^*/dx$, the asymmetry of the VAWT wake, and hence the asymmetry of the profiles, has been taken into account by including the term $d\delta_o^*/dx$. This term is able to implement the features of the VAWT wake in the Reynolds stress normalizing function. Figure 4.12 shows normal and shear Reynolds stress components scaled using $U_\infty^2 d\delta_o^*/dx$. The downstream profiles of $\overline{u'u'}$ before $x/D = 2.5$ are closer to each other than the ones beyond this point in x . This behavior is expected for a VAWT wake given the two distinct regions. Profiles of the remaining Reynolds stresses are closer to each other, especially in the near wake, where they collapse with the exception of $\overline{w'w'}$ component. The two downstream regions are distinguished for all the stress components. $\overline{u'w'}$ and $\overline{u'v'}$ components of Reynolds stress show an excellent receptivity to the scaling in both

Figure 4.11: $\overline{u_i u_j}$ components of Reynolds stresses normalized by U_∞^2 .

regions. The profiles before $x/D = 2.5$ are close to a collapse, and the profiles after $x/D = 2.5$ almost collapse on top of each other. The latter behavior is suggesting again that the shear Reynolds stresses profiles are more likely to approach collapse than the normal stresses.

The turbulence kinetic energy, k , is also used to normalize Reynolds stresses. The $\overline{u'u'}$ component of Reynolds stresses scaled by k is shown in Figure 4.12. The profiles come significantly closer to each other and almost show a collapsed state capturing both wake regions profiles. Beside the collapse of the curves, there is a change in the Reynolds stress profiles in the negative z part of the wake, where the peak between $(z - z_o)/\delta_o^* = 0$ – (-40) flattens.

All the remaining Reynolds stresses normalized by k in Figure 4.13 exhibit similar behavior as the $\overline{u'u'}$ component. The profiles display the best collapse by falling on top of each other for the entire wake. Reynolds shear stresses show better tendency to collapse in

Figure 4.12: $\overline{u_i u_j}$ components of Reynolds stresses normalized by $U_\infty^2 (d\delta_o^*/dx)$.

the first region of the wake than the normal stresses, though both scale well at the second region.

In parallel, Figure 4.14 shows a comparison between the three scaling methods used to scale $\overline{u'w'}$ Reynolds stress. U_∞^2 brings the curves slightly closer to each other than $U_\infty^2 (d\delta_o^*/dx)$ does. Furthermore, it scales the very near wake significantly better than $U_\infty^2 (d\delta_o^*/dx)$ does. However, the third scaling function k collapses all profiles on top of each other making k the best option for scaling the Reynolds stresses in this particular flow. All the scaling methods have a better effect on the shear stresses than on the normal stresses due to having u velocity component in the normalizing function, and that explains the better response of the normal stresses to the third scaling, k , that not only has u in it, but also v and w fluctuating components giving it the ability to remove the variations in the Reynolds stresses that are caused by these components. On another hand, k offsets the effect of the turbulence kinetic energy of the stress field overcoming by that another cause

Figure 4.13: $\overline{u_i u_j}$ components of Reynolds stresses normalized by k .

Figure 4.14: Comparing the three Reynolds stress scaling functions plotted against $(z - z_0)/\delta_o^*$ as the spanwise coordinate.

that contributes to the Reynolds stress profiles change downstream. The later feature is one more advantage that k has over the other scalings.

4.2.3 Summary

PIV data are collected behind a model VAWT in a wind tunnel experiment. The data are used to observe and examine the wake features and development downstream. Furthermore, scaling of mean velocity deficit as well as Reynolds stresses is conducted.

The wake asymmetry is apparent and the direction of its skewness is with the rotor rotation. The part of the wake in the rotation direction experiences faster expansion as the momentum is convected in this direction by $\overline{u'w'}$ and $\overline{v'w'}$ Reynolds stresses. The rotation of the rotor influences the wake such that the wake has two significant regions downstream before and after $x/D=2.5$. The wake in the latter region displays reduced wake expansion and velocity deficit.

Scaling the velocity deficit normalized by U_o , $(z - z_o)/\delta_o^*$ proves to be an appropriate spanwise coordinate to collapse downstream profiles as it compensates for the wake shift. Scaling the Reynolds stresses on the other hand is more challenging and requires further examination. Three functions are employed to normalize Reynolds stress and compared in order to determine the function appropriate to collapse downstream profiles.

Using U_∞^2 to normalize Reynolds stress is not an effective scaling. The profile come slightly closer to each other, but no significant tendency to collapse especially the near wake region ($x/D < 2.5$). The region after $x/D=2.5$ profiles at the thicker part of the wake are marginally closer than at the thinner part.

The second scaling investigated is $U_\infty^2(d\delta_o^*/dx)$. The $d\delta_o^*/dx$ term is embedded to offset the variation of Reynolds stresses caused by the wake skewness. The addition of the later term improves the scaling compared to U_∞^2 . Reynolds shear stresses response relatively better to scaling. $\overline{w'w'}$ component of Reynolds stress shows a reduced aptitude to collapse. Reynolds stress profiles collapse when normalized by the turbulence kinetic

energy k . Both regions before and after $x/D=2.5$ response adequately to the scaling as k absorbs the kinetic energy that causes variation downstream. Similarly, as the thinner part of the wake (in the positive z direction) has higher level of turbulent kinetic energy than the thicker part, both parts of the profiles collapse to k scaling. Reynolds shear stresses show marginally better collapse than normal stresses. $\overline{w'w'}$ component scales significantly well to k scaling especially compared to its modest response to the other normalizing parameters. Being able to scale a VAWT asymmetric wake is a step forward in facilitating the exploitation and growth of these turbines in wind energy sector mainly by reducing the spacing between turbines. Wake development of wind turbines is a prime factor in wind farm setups.

4.3 Floating Wind Turbines ³

The time resolved hot-wire data described in Section 3.3 is used to conduct EMD-HHT and intermittency analysis. Intermittency leads to added dynamic loading on turbine structure and fluctuation in power output.

4.3.1 Flow characteristics and identification of scales

Figure 4.15 shows the scaling exponent ξ_4 at different vertical locations obtained from the fourth order structure function in the near wake one diameter downstream fixed and pitching turbines under passive and active grid inflow conditions. The 3rd order structure function S_3 contains no intermittency, hence, the 4th order structure function S_4 is plotted against S_3 , then the slope between the two yields the scaling exponent ξ . K41, is plotted

³ The following results are adapted from, Kadum, H., Rockel, S., Hölling, M., Peinke, J. and Cal, R.B., 2019. Wind turbine wake intermittency dependence on turbulence intensity and pitch motion. Journal of Renewable and Sustainable Energy, 11(5), p.053302.

Figure 4.15: Fourth order scaling exponent ξ_4 one diameter downstream pitching and fixed turbines for passive and active grid inflow conditions.

for reference and the divergence of the estimated scaling exponent from that reference is a measure of intermittency as it represents the intermittency correction Δ . For active grid, the pitching turbine is more intermittent. The difference in intermittency level between pitching and fixed wind turbine is more pronounced at the locations where the flow is less turbulent (lower turbulence intensity), the top tip in this case as the turbulence caused by tip vortex shedding has moved to above top tip due to the upwards shift of the PWT wake [Rockel et al., 2017]. The effects of active grid (flow with increased turbulence intensity) overshadows the effects of pitch motion. The locations where the wake of PWT experiences the effect of tip vortex shedding, above top tip, show less variation from the fixed turbine as the effects of pitch induced intermittency are damped by the flow turbulence. This behavior coincides with the findings by Ali et al. [Ali et al., 2016a].

When the grid is passive, the flow is less turbulent in general due to lower turbulence intensity. The difference between pitching and fixed turbine intermittency is significantly

more pronounced as the pitch motion effects are apparent in this case. The scaling exponent ξ of pitching turbine is 54% higher than that of the fixed turbine for the passive grid case, whereas for the active grid case, it is only 5% higher at the top tip. There, the intermittency caused by tip vortex shedding turbulence of the fixed turbine is superior to the pitch induced intermittency of the pitching turbine. The Fourier spectra of the inflow is presented in Figure 4.16 for the passive and active grid conditions showing the $-5/3$ power law trend. As the passive grid case is when the pitching motion more apparent, the downstream development of the Fourier spectra is shown in Figure 4.16 (a) through (d) at the top tip location. The energy peaks propagate downstream, however, the peaks corresponding to the pitching wind turbine are more persistent than the fixed wind turbine.

Figure 4.16: Fourier Spectra for passive and active grid inflow as well as the wake flow at several downstream locations for fixed and pitching wind turbines at the top tip. The dashed black lines indicate $-5/3$ power law.

Intermittency variation depending on the location and inflow condition poses the question of turbulence characteristics at different scales. The energy contained in pitching wind turbine wake scales is observed through its premultiplied energy spectra (PMS) in Figure 4.17. The premultiplied energy spectra, $(k_x \phi_{(uu)}/U^2)$, are calculated by using a fast Fourier transform (FFT) algorithm. Taylor's hypothesis is employed to convert en-

ergy spectra from frequency domain into length scale and wavelength representation, the variables λ_x , f , $U(x)$, and k_x are wavelength, frequency, mean velocity, and wave number in the streamwise direction, respectively [Tang et al., 2012, 2016, 2017]. Premultiplied energy spectrum contours in vertical location-wave number domain are presented. The passive grid case is displayed as the pitch motion effects are more pronounced in this case. A shift between the contours lines of the two turbines increases towards smaller scales suggesting that the same amount of turbulence kinetic energy of a fixed wind turbine is contained in smaller scales compared to pitching wind turbine, see Figure 4.17(b) and (c). The PMS contour of level 14 (grey color) extend over wavenumbers $k = 1000$ to $k = 1700$ between the hub height and the bottom tip in the fixed wind turbine. In the pitching wind turbine, the same level of PMS extends over wavenumbers $k = 1500$ to $k = 2500$. The projected area of the pitching wind turbine rotor being smaller than the fixed turbine as well as its constant interruption of the flow due its oscillations causing the flow to have smaller scales. Large scales, on the other hand, show the effects of pitch motion as distributed peaks seen on the pitching turbine contours indicating that different scales respond differently to pitch motion. Large scales are associated with high turbulence kinetic energy content. The pitch effects found at the pertaining scales suggests that the pitch motion adds to the flow turbulence resulting in energy rise in the flow that is contained in the larger scales. This conclusion coincides also with the existence of peaks around and above the top tip where tip vortex shedding takes place, and contributes similar, though less frequent, fluctuations in the PMS contours of the fixed turbine.

To further investigate the properties of flow scales and their reaction to the presence of the turbine, an arbitrary flow signal decomposed into large scales ($L_s \geq 0.05D$) and small scales ($S_s \leq 0.05D$) is presented. The scale $0.05D$ is chosen as an arbitrary scale of value

Figure 4.17: Premultiplied energy spectrum for (a) inflow in contour representation, (b) wake flow in contour representation, and (c) Wake flow in one dimensional representation. The wake flows are 1D downstream location for fixed (grey scale) and pitching (parula scale) wind turbines subjected to passive grid inflow condition superposed on top of each other for comparison.

between the integral and Taylors length scale (the scale where kinetic energy dissipation starts occurring) for illustration purposes. In Figure 4.18, the signal is decomposed using low pass filtering and fast Fourier transformation. Here, the large scale signal has the same peak magnitudes as the original signal, whereas the small scale signal conveys the small fluctuations of the original signal. Even though the velocity fluctuations are reduced in number in the large scales signal, the fluctuations caused by turbine oscillations are easily distinguished. The latter observations, along with the PMS contours, highlight the

importance of examining scales of interest, large scales in this case, rather than the general flow.

Figure 4.18: Arbitrary time series decomposed into large and small scale signals using low pass filtering. $S_s \leq 0.01 \text{ m}$ and $L_s \leq 0.01 \text{ m}$, where $0.01 \text{ m} = 0.05D$.

4.3.2 Empirical Mode Decomposition

In order to be able to study scales separately and to conduct HSA, herein, the flow is decomposed to different scales using EMD. The empirical mode decomposition yield 21 intrinsic mode functions for each time series. The IMFs correspond to narrow bands of frequencies of descending order. In Figure 4.19, some of the highly correlated IMFs are examined to reveal their physical meaning. They correspond to the inflow and wake flow $1D$ downstream the top tip position in passive grid case. IMF4 contains fluctuations in the near wake of the fixed wind turbine that are not present in the inflow. The fluctuation occurs at time scales roughly around 0.02 sec and they are believed to correspond to tip vortices. Similar events are observed in the fourth IMF of the pitching wind turbine yet they include additional more organized, higher amplitude fluctuations that occur in frequency of $53 -$

56 Hz equal to the rotational frequency of the rotor [Rockel et al., 2017]. For this specific location with mean velocity of 4.6 m s^{-1} , the time scale relates to a length scale of $0.42D - 0.46D$. The distance traveled by the turbine tip can be approximated as the turbine height 0.34 m times the $\sin \theta$. For $\theta = 15^\circ$, the distance is 0.088 m ($0.44D$) that falls in the range of scales caused by the frequencies observed in the fourth IMF. These observations suggest the pitch motion adding scales to the flow in the order of the rotor radius and that the physical nature of these events is similar to a tip vortex shedding in a fixed turbine but happening with larger magnitudes and more orderly manner. If one thinks about the pitching motion as a turbine that is moving in a flow field (as the turbine retracts to its equilibrium position), then it is reasonable to think the tip interaction with the flow is generating events that are similar in nature to events happening when the flow is moving towards a fixed turbine. Similar analogy can be applied to IMF5 which also contains tip vortices and pitch motion feature. The magnitude of the pitch fluctuations is not constant caused by different stages of the pitching motion [Lei et al., 2019]. The larger magnitude correspond to the stage where the turbine is at the maximum angle downstream, while the small magnitudes correspond to the equilibrium position when the turbine is perfectly vertical at pitching angle $\theta = 0^\circ$.

Fourier spectrum is then employed to determine scale range to which each IMF belongs. Figure 4.20 presents Fourier spectra of IMFs decomposed from the flow one diameter behind pitching turbine at top tip since Figure 4.15 showed more activity of pitch motion at top tip. The IMF Fourier spectra allow identifying the integral length scale by noting the start of the inertial subrange which has the highest energy. IMFs 3 through 8 belong to the inertial subrange as their distribution agrees to $-5/3$ power law. Figure 4.20 (a) and (b) reveal the scales affected by pitch motion. In Figure 4.20 (a), there are some

Figure 4.19: The fourth IMF for the incoming flow (top) and the fourth, fifth, sixth, and eighth IMFs for the wake flow at the top tip location $1D$ downstream fixed and pitching turbines under passive grid inflow condition.

peaks in the large scales correspond to tip vortex shedding. However, in Figure 4.20 (b), the number of peaks significantly increases compared to fixed turbine case suggesting that the pitch motion effect is conveyed as energy increments observed as peaks in the energy spectrum. The latter peaks are spread over a broader range of scales (IMFs 3 to 8) compared to the peaks caused by tip vortex shedding existent only in IMFs 6-8. The frequency of pitch motion perturbations is 55 Hz and its harmonics on average; the perturbations coincide at the same frequencies for all the IMFs within the inertial subrange. This observation proves that the pitch motion is adding, as well as affecting, large scales of the flow which in turn explains the existence of peaks at and above the top tip in the pre-multiplied spectrum contours located at the low wave numbers region. The pitch perturbations correspondent to active grid case, Figure 4.20 (d), are less pronounced when compared

to the passive grid case; observed only in IMFs 6 to 8 which is believed to be due to the active grid increases the turbulence of intermediate scales, IMFs 3 to 5, damping the pitch motion effects at these scales.

Figure 4.20: Fourier energy spectrum for different IMFs 1D downstream the top tip for (a) Passive-fixed (b) Passive-pitching (c) Active-fixed (d) Active-pitching turbines.

4.3.3 Hilbert spectral analysis

The first step of the HSA is to transform the IMF signals into local energy amplitudes and local frequencies, which will later be used to obtain Hilbert marginal spectra, the key step to computing the Hilbert scaling exponent for intermittency computation. Marginal

Hilbert spectrum is shown on a log plot in Figure 4.21 for the inflow and 1D downstream of the fixed and pitching turbines for vertical locations at and above top tip. The inflow and near-wake spectra coincide with Fourier energy spectrum by following $-5/3$ power law, hence, it is proved to be representative of the flow characteristics. The active grid spectra for both fixed and pitching turbines have energy higher than the passive grid cases above top tip caused by the higher turbulence imposed by the active grid. Nonetheless, the pitching turbine carries the highest energy content between the two active cases. At the top tip however, active and passive grid spectra have comparable energy amplitudes demonstrating the dominance of rotor tips impact over inflow condition impact at that location.

Figure 4.21: Marginal Hilbert spectrum $h(f)$ one diameter downstream fixed and pitching wind turbines for passive and active grid inflow conditions.

Arbitrary order spectrum analysis based on Hilbert Huang transform is conducted to observe the turbulence cascades for the various cases by estimating Hilbert scaling exponents, which can be compared to the structure function approach. Figure 4.22 presents the second order marginal Hilbert spectrum $\mathcal{L}_2$ estimated at bottom tip, top tip, and above top tip for passive and active grid cases as well as for pitching and fixed wind turbines. The Figure shows that at *BT* both fixed and pitching turbines have the same turbulence cascade

with a slope of $\zeta_2 \simeq 2$. Marginal difference in the slope is noticed at the top tip besides the fact that the inertial subrange started at a larger scale in the pitching wind turbine than when is fixed. The difference in the inertial subrange behavior is more pronounced above the top tip with slopes $\zeta_2 = 2.75$ and $\zeta_2 = 2.56$ for the fixed and pitching wind turbines respectively. This is believed to be related to a larger structure forming above the top tip and that the pitching turbine fluctuations have higher influence over larger scales. For the

Figure 4.22: Second order marginal Hilbert spectrum for inflow and wake flow at 1D downstream location at three vertical positions: bottom tip *BT*, top tip *TT*, and above top tip *ATT* (from left to right). Top row shows Hilbert spectra for fixed and pitching wind turbines in passive grid inflow condition. Bottom row shows Hilbert spectra for pitching wind turbines in passive and active grid inflow conditions.

active grid case, the inertial subrange of the *BT* still exhibits almost the same slope of $\zeta_2 \simeq 2$. Moving up across the rotor, the turbulence intensity effects are higher. At the *BT*, the effects are confined to frequencies higher than 10^{-4} Hz, whereas at the top tip they extend as far as integral length scales around 10^{-2} Hz. The entire cascade is influenced by the active grid above the top tip. The scaling exponent is estimated from the q^{th} order marginal Hilbert spectrum $\mathcal{L}_q$ slope as $\xi_q = \zeta_q - 1$. For a monofractal flow, the $\xi(q)$ versus q curve is linear. A nonlinear curve is an indicator of multifractality, hence, intermittency. Using

the slope between q and scaling exponent, a fractal system can be described as monofractal (homogeneous) or multifractal (heterogeneous). Monofractal flows are described by a singular unique scaling exponent, in contrast to the multifractal systems that are labeled by a continuum of scaling exponents. Mathematically, monofractality and multifractality mean that the slope between the moment q and the scaling exponent is linear and nonlinear respectively. Physically, the scales of a monofractal flow are self-similar meaning the flow is scale invariant. See Ali et al. [Ali et al., 2016b] Meneveau et al. [Meneveau and Sreenivasan, 1987], and Chevillard et al. [Chevillard et al., 2006] for more details related to multifractality in turbulent flows. The scaling exponents at various vertical locations for the fixed turbine at passive grid condition are plotted in Figure 4.23 for $q = 0 - 6$. The Figure shows that the scaling exponent is significantly nonlinear at the TT compared to other locations. The scaling exponent curves for fixed and pitching wind turbines in low turbulence intensity flow (passive grid) are shown in Figure 4.23 (middle column). The pitch motion effects are apparent at and above the top tip. The scaling exponents for pitching and fixed wind turbine exhibit a significantly non-linear trend. The fixed wind turbine displays more non-linearity due to the tip vortex shedding associated with that location. On the other hand, above the top tip, the pitching wind turbine scaling exponent curve is more non-linear than the fixed. Amongst the three locations, scaling exponent profiles at top tip location are most non-linear for both turbine types due to the tip vortex shedding occurring at that particular location increasing multifractality.

Figure 4.23: Scaling exponent $\xi(q)$ estimated via Hilbert spectral analysis (HSA) at different vertical locations (left column), for pitching and fixed wind turbines in low turbulence intensity (middle column), and for pitching wind turbine in high and low turbulence intensity flow (right column).

In Figure 4.24, the HSA based scaling exponent $\xi(q)_{HS}$ is compared to the structure function based scaling exponent $\xi(q)_{SF}$ and to the theoretical scaling exponent $\xi(q)_{TH}$ computed theoretically using the equation $\xi_q = \mathcal{H}q - 1$, where $\mathcal{H} = \xi_1 - 1$. The divergence of SFA and HSA scaling exponent curve from the theoretical case is an indication of intermittency. Both methods agree on the multifractality of the flow. The scaling exponents estimated using the two methods coincide with each other at the *BT* for both turbine types, however, a significant difference can be observed between the two when moving to *TT* and *ATT*. This difference shows that the HSA more accurately estimates the scaling exponent than the SFA approach since it is occurring at the location where larger structures are forming. The scaling exponent versus q curves are expected to be convex as the scaling exponents are mathematical Laplace characteristic functions. The estimations of the scaling exponents using structure functions can be contaminated when the flow has energetic scales leading to less accurate results. Huang et al. [2010] found that the struc-

ture function approach estimation of the scaling exponent is significantly influenced by the large scales of the flow as their contribution is up to 79% extended over 1.4 decades of the frequency domain versus 0.3 for the Hilbert spectral analysis. The deformation of the convex trend of the structure functions curves shown in the Figure 4.24 reveals the influence of the energetic scales and how that leads to less accurate representation of the Laplacian scaling exponent function. For the pitching wind turbine, the upshift of the wake makes the formation of large coherent structures moves up to above the top tip resulting in the overestimation of the SFA scaling exponent more pronounceable at ATT than TT . A summary of the intermittency computed as the difference between the sixth order theoretical scaling exponent and the scaling exponent obtained via HSA is presented in Table 4.1.

Figure 4.24: Scaling exponent estimated via structure function and Hilbert spectral analysis superposed to the theoretical scaling exponent for inflow and wake flow at 1D downstream location at three vertical positions: bottom tip BT , top tip TT , and above top tip ATT (from left to right). Top row shows scaling exponents for fixed wind turbine and bottom row shows scaling exponents for pitching wind turbines in passive grid inflow condition.

Table 4.1: Summary of the intermittency computed as the difference between the sixth order theoretical scaling exponent and the scaling exponent obtained via HSA ($\xi_{TH6} - \xi_{HS6}$) for passive grid inflow condition.

Study case / Location	Bottom tip	Top tip	Above the top tip
Pitching wind turbine	1.351	3.345	0.794
Fixed wind turbine	1.373	2.772	0.659

4.3.4 Summary

Hot-wire data are collected behind fixed and pitching wind turbine models in a wind tunnel experiment. EMD-HHT analysis is applied to extract the wake features including the pitch motion. The arbitrary order marginal Hilbert spectral analysis is conducted to investigate the flow scales intermittency characteristics. First, the effectiveness of HHT approach in describing the flow energy amplitudes and scales is validated by generating Fourier energy spectra plots of each IMF decomposed from the original signal. The data exhibited $-5/3$ power law demonstrating typical turbulent flow energy cascade behavior. The intermittency of the cases studied, two turbine types and two inflow conditions, is first examined using fourth order structure function. The scaling exponent is more dependent on the pitch effect when the flow is less turbulent. Also, it shows that the pitching wind turbine has higher intermittency level across the vertical location, except at the top tip where the vortex-shedding intermittency of the fixed wind turbine is higher than the pitch-induced intermittency of the pitching wind turbine.

A premultiplied energy spectrum analysis is also conducted to see how different scales respond to pitch motion. A shift is noticed between PMS contours of fixed and pitching wind turbine that increases with wave number suggesting that for pitching wind turbine, the same amount of energy is contained in smaller scales than fixed wind turbine. Further-

more, the contours are significantly perturbed at the top tip, seen as peaks in the contours lines concentrated in the large scales region. The fixed turbine contours are perturbed due to tip vortex shedding, while the pitching turbine contours are significantly more perturbed, and it is caused by pitch motion. The EMD analysis was able to extract the pitch motion features and it revealed that its effect on the flow is similar to tip vortex shedding. The Fourier energy spectrum of the different scales agrees with the PMS contours that the intermediate-large scales are more affected by pitch motion due to the oscillation being on the order of the rotor radius as they happen at a frequency of 55 Hz and its harmonics down to scales that are larger than Taylor microscale.

Arbitrary order Hilbert spectrum analysis suggests that the pitch motion effects on the second order Hilbert spectrum (marginal Hilbert spectrum) are apparent at and above TT . Also, increasing the turbulence intensity of the flow has a significant effect on the $\mathcal{L}_2$ behavior and the range of scales influenced by this effect extends from small scales at BT to the entire cascade ATT . The scaling exponent estimated using arbitrary order Hilbert spectrum analysis shows that the top tip has the highest multifractality. Furthermore, the flow behind a pitching wind turbine is more intermittent than the flow behind a fixed wind turbine above the top tip while the opposite is true at the top tip. Increasing turbulence intensity increases the multifractality of pitching wind turbine at top tip and more above top tip. It was proven that HSA is a more accurate way of estimating the scaling exponent than SFA due to the latter being influenced by the energetic scales in the flow.

This work enhances the understanding of turbulence characteristics of offshore wind turbine wakes. It presents a description of pitch motion impact, its location, the relative scales influenced by it as well as the conditions which enhance or reduce these effects. Power production, fatigue loading, and pitching platforms design of these wind farms

depend significantly on the wakes from proceeding turbines as well as the flow features generated due to the operating condition of the turbine itself. Analysis of the turbulence cascade and its power law is a step forward the characterization of these flows. Pitch motion is one of six degrees of freedom that offshore wind turbines experience, which calls for further work dealing with these motions individually as well as in conjunction. As the current study indicates an increase in intermittency due to turbine pitching, low order statistical analysis to quantify the intermittency coefficients is recommended for future work, though the use of Hilbert spectral analysis for intermittency evaluation is preferred over structure functions analysis for flows with complicated events.

4.4 Assessing Intermittency in Floating Turbines via Cumulant Analysis ⁴

Magnitude cumulant analysis is used to evaluate intermittency in a floating wind turbine wake and the wake between two floating wind turbine. This analysis is used as a low-order moment approach to obtaining intermittency.

4.4.1 Methods validation and inflow characterization

To validate the methods used to compute the cumulants and the experimental measurements, magnitude cumulants are shown for direct numerical simulations (DNS) of homogeneous isotropic turbulence. This data set is used herein as it has been shown in previous studies [Chevillard et al., 2005] that the second cumulant typically displays three scaling regions: Far dissipation range, near dissipation range, and inertial subrange. The inertial range was shown to follow a slope of $-c_2 = -0.025$. The same region follows a slope of

⁴The following results are adopted from, Kadum, H., Rockel, S., Viggiano, B., Dib, T., Hölling, M., Chevillard, L., and Cal, R.B., submitted to Chaos, Solitons & Fractals.

$c_1 = 1/3 + 3c_2/2$ in the first cumulant profile, while the far dissipation range exhibits a -1 slope. Figure 4.25 presents the first and second order magnitude cumulants for the DNS data. The vertical axis in the second cumulant represents $C_2(\tau) - (\pi^2/8)$, but referred to as $C_2(\tau)$ throughout the paper for simplicity. The second order coefficient c_2 is referred to as intermittency coefficient for herein. The figure shows the regions described earlier [Chevallard et al., 2005] confirming the accuracy of the method for computations.

Figure 4.25: First and second order cumulants of a DNS data set for isotropic flow field.

The methods are applied to characterize the inflow of the experimental data set used in this work. Figure 4.26 presents the cumulants for the two inflow conditions generated using active and passive grid arrangements. The cumulants at each time scale τ are plotted against the time scales normalized by the separation time scale τ_s , the scale at which the inertial range ends and the second cumulant asymptotes. Two vertical dashed lines are used to indicate the inertial subrange over which the cumulant slopes are obtained. The inflow exhibits typical cumulant profiles and the inertial range is identified. The inertial range has an intermittency coefficient of $c_2 = 0.023$ and $c_2 = 0.026$ in the passive and active grid flow, respectively, and the first cumulant coincides with $c_1 = 1/3 + 3c_2/2$ in that region.

Figure 4.26: First and second order cumulants for the inflow generated using passive and active grid.

4.4.2 Turbine type and turbulence intensity

To assess the effect of pitch motion on flow intermittency, Figure 4.27 presents the first and second cumulants of a floating wind turbine compared to a fixed wind turbine. The pitch motion effects have been found to be more apparent in flows with lower turbulence intensity [Kadum et al., 2019b], hence the passive grid case is presented in Figure 4.27. The figure shows that interaction with the wind turbine increases flow intermittency in the near wake. The intermittency coefficients are $c_2 = 0.041$ and $c_2 = 0.048$ for the fixed and floating wind turbines, respectively. These values are at least 60% higher than ≈ 0.025 in the inflow. The results also suggest pitch motion increasing the intermittency by about 17% at that location compared to the fixed wind turbine.

The impact of inflow turbulence intensity on floating wind turbine intermittency is presented in Figure 4.28. The figure shows an increase of 14% in intermittency when the inflow turbulence intensity of the inflow increased from 1.8% to 15.9%. The structure of a wind turbine in a floating wind farm setting is hence enduring more dynamic loads caused by the turbine oscillations that increase with increased flow turbulence intensity. It is then necessary to account for the additional intermittency when modeling a floating

Figure 4.27: First and second order cumulants for a fixed and floating wind turbine in passive grid condition. The cumulant is computed 1D downstream bottom tip location.

wind turbine wake and when predicting its lifespan.

Figure 4.28: First and second order cumulants 1D downstream the bottom tip of a floating wind turbine under passive and active inflow conditions.

4.4.3 Vertical location dependence

The results presented above correspond to the bottom tip location. However, it is recognized that wind turbines wake flow varies significantly depending on the location along the turbine height. The top tip location is associated with complex aerodynamics, thus Figure 4.29 demonstrates the cumulants at this location in the near wake. The second cumulant profile does not accurately identify the inertial range as the profile does not coincide with a slope close to -0.025 , and no region in the first cumulant profile aligns

Figure 4.29: First and second order cumulants 1D downstream the top tip of a floating and a fixed wind turbine under passive inflow conditions.

with $c_1 = 1/3 + 3c_2/2$. The profiles exhibit high-intensity undulations after the dissipation range, making it challenging to detect the inertial range. The undulations are existent in both turbine types and believed to be caused by flow dynamics associated with rotor tip location like tip vortex shedding. These undulations will be referred to as tip-effect fluctuations hereon. The tip-effect fluctuations suggest non-local scale interactions that leads to perturbations in the scaling cascade as observed in the top tip cumulant profiles. Tip-effect fluctuations do not exist at the bottom tip location due to the turbine nacelle blocking the flow preventing any non-local scale interactions from occurring.

Figure 4.30: First and second order cumulants 1D downstream the location 0.165D above the top tip of a floating and a fixed wind turbine under passive inflow conditions.

The floating wind turbine profiles displays additional fluctuations, hence they are

caused by the pitch motion. Similar behavior is observed in the flow immediately above the top tip location, see Figure 4.30. These results suggest that the intermittency in those specific locations is hard to quantify using cumulant analysis or any scaling-dependent approach. Whether this conclusion is true for other downstream locations is investigated in the following subsection. Nevertheless, it is recommended to use alternative techniques to evaluate intermittency in near rotor tip locations like Hilbert - Huang analysis [Kadum et al., 2019b, Schmitt et al., 2009].

4.4.4 Downstream development

The results so far concern the flow near the wake, specifically $1D$ downstream the turbines. The intermittency development up to $7D$ downstream is examined herein. Figure 4.31 presents the first and second cumulants of a floating wind turbine in a passive grid inflow condition. The cumulants are obtained for wake flow $1D$, $3D$, $5D$, and $7D$ behind the top tip. The inertial range is not identified even at $3D$ downstream the rotor due to tip-effect fluctuations in the profiles propagating further downstream. At $5D$, these fluctuations diminish, and the inertial range is apparent. The intermittency at $5D$ is 28% higher than the inflow with $c_2 = 0.032$, and the intermittency added to the flow due to interacting with the turbine persists up until $7D$ behind the turbine where $c_2 = 0.025$. The intermittency caused by tip-effect fluctuations, and flow-turbine interaction in general, dissipates gradually before vanishing seven rotor diameters downstream the turbine.

In Figure 4.32, the downstream development of cumulants and intermittency for a floating wind turbine in an active grid inflow arrangement is presented. The figure highlights an interesting finding of higher turbulence intensity flow. Although the active grid case resulted in higher intermittency than the passive grid at $1D$, Figure 4.32 shows that the

Figure 4.31: Downstream development of cumulants at the top tip of a floating wind turbine under passive grid inflow condition.

active grid leads to faster recovery of the flow in terms of tip-effect fluctuations caused by tip vortex shedding and pitch motion. The inertial range is identified at $5D$ downstream of the turbine in the passive grid case, whereas in the active grid case the range is clearly observed at $3D$. Furthermore, the intermittency level at this location is equal to the intermittency level of the passive grid case at $5D$ where their intermittency coefficients are $-c_2 = -0.033$ and $-c_2 = -0.032$, respectively. Meaning that the higher turbulence intensity can break any flow structures caused by the pitch motion faster generating a flow with linear turbulence scales cascade in the inertial subrange.

Figure 4.32: Downstream development of cumulants at the top tip of a floating wind turbine under active grid inflow condition.

Downstream development of intermittency for a fixed wind turbine is examined in

Figure 4.33. Similar to a floating wind turbine, the inertial range scaling is recovered $3D$ downstream of the rotor in an active grid inflow condition. The difference in intermittency between floating and fixed wind turbines found at $1D$ downstream the rotor is marginal at $3D$, where the aforementioned turbines have intermittency coefficients of $-c_2 = -0.032$ and $-c_2 = -0.03$, accordingly.

Figure 4.33: Downstream development of cumulants at the top tip of a fixed wind turbine under active grid inflow condition.

4.4.5 Two merging wakes

Here, the flow intermittency $1D$ downstream merging wakes generated by two aligned turbines is examined. Figure 4.34 shows the second cumulant at selected locations illustrated in the schematic provided on the right side of the figure. Points located near the rotor tips, P_1 and P_{11} , experience the tip-effect fluctuations observed in the top tip and above the top tip locations in the single wind turbine wake. The inertial range is thus hard to identify and the intermittency coefficient can not be accurately obtained, the inertial subrange is also not observed in the first cumulant profile (not shown). It is noted that location P_1 experiences lower tip-effect fluctuations than location P_{11} even though they are equally distanced from the rotor tips, suggesting dependency on the turbine rotation direction. The locations to the positive side of the rotation direction ($+z$) undergo higher rotor tip effects compared

to the points on the $(-z)$ side. Location P_9 behind the rotor hub exhibits a typical second cumulant trend with an intermittency coefficient $c_2 = 0.025$. The wakes merging locations P_5 , P_6 , and P_7 are presented in the lower three subfigures. Locations P_5 and P_7 are near rotor tips, however, unlike in locations P_1 and P_{11} , the tip-effect fluctuations do not appear in their profiles.

Figure 4.34: Second order cumulants at various spanwise locations $1D$ behind two floating wind turbines under passive grid inflow conditions.

This observation is evidence of damping happening when two wakes meet. In addition to damping the tip-effect fluctuations, the intermittency is also lowered compared to the near wake of a single wind turbine. For a bottom tip location $1D$ behind a single wind turbine, the second cumulant coefficient is $c_2 = 0.048$ for a flow with 1.8% turbulence intensity. For a flow with 4% turbulence intensity near rotor tip locations at P_5 and P_7 , the second cumulant coefficient for two merging wakes are $c_2 = 0.023$ and $c_2 = 0.033$, accordingly. Merging wakes reduces extreme events in the wake flow helping wind farms reduce intermittency compared to a single wind turbine. This is even more evident at the center of merging wakes, represented by location P_6 in Figure 4.34. Location P_6 has a negligible second order coefficient of $c_2 = 0.0068$ which is an order of magnitude lower than other locations. The aforementioned findings are an advantage for staggered wind

farms where the turbines of one row are located in the wake-merging regions of a previous row.

4.4.6 Non-analytical cumulant analysis

Non-analytical cumulant results are presented in Figure 4.35. the parameters α and C_α are obtained by curve fitting the function $\phi(q) = C_\alpha q^\alpha$ to a power law function as shown in Figure 4.35. The function $\phi(q)$ is obtained as described in equation 2.34. The left and right columns of subfigures correspond to hub height (HH) and top tip (TT) locations. The first row of subfigures correspond to a fixed wind turbine, while the floating wind turbine results are presented in the second row.

Figure 4.35: Non-analytical cumulant for fixed (top row) and floating (second row) wind turbines in passive grid case at the hub height (left column) and top tip (right column) locations.

The function $\phi(\tau, q)$ exhibits a convex trend typical for power functions when plotted against q , which shows linear behavior when plotted in log-log scale. Figure 4.35 shows the $\phi(\tau, q)$ function for various random scales within the inertial range. Although marginal, the function profile curvature decreases when the scales are larger. The non-analytical exponent α has a scale-universal value of 1.3 ± 0.14 , which remains unchanged when altering the inflow condition or the turbine type. This value is lower than the range of $1.58 - 1.8$ estimated in other studies on different turbulent flows [Michalec et al., 2015, Schmitt et al., 2009], and thus indicating more intermittent flow. The non-analytical cumulant C_α presents variation with vertical location, though marginal. An average value of $C_\alpha = 0.7 \pm 0.02$ and $C_\alpha = 0.8 \pm 0.02$ is obtained at the hub height and top tip locations, respectively. Furthermore, the C_α profile displays similar tip effect fluctuations towards the inertial range that are more notable in the passive grid case.

4.4.7 Summary

The current study examines intermittency in wind turbines experiencing pitch motion using magnitude cumulant analysis. The results show the inflow possessing a typical second cumulant coefficient $c_2 \approx 0.025$. When the flow interacts with the turbine, an increase of at least 60% from that value is found $1D$ downstream of the rotor. The pitch motion results in 17% higher intermittency in the floating wind turbine compared to the fixed wind turbine. The study also reports an increase in intermittency coefficient of 14% when the inflow turbulence intensity is increased by 78%.

Non-local scale interactions are observed near the rotor tips, except the bottom tip. These interactions cause tip-effect fluctuations in the cumulant profiles. The pitch motion is found to cause additional fluctuations that are only found in the floating wind turbine

wake. The tip-effect fluctuations lead to difficulty identifying the inertial subrange, hence, the intermittency is not obtained for those locations in the near-wake flow.

For the passive grid inflow condition, the tip-effect fluctuations travel up until $5D$ downstream of the rotor. Interestingly, higher turbulence intensity is found to speed the dissipation of tip-effect fluctuations. For that active grid case, these fluctuations travel only $3D$ downstream. Furthermore, after $3D$ the active grid flow no longer causes higher intermittency than the passive grid as both cases are found to have equal intermittency coefficients of $c_2 \approx 0.033$. The same is true for the pitch motion. Floating and fixed wind turbines have equal intermittency coefficients after $3D$ downstream. The latter observation suggests that the intermittency caused by pitch motion of a single turbine does not impact turbines in a successive row, although the pitch motion of each turbine still impacts that same turbine. This behavior needs to be further tested in a wind turbine array setting.

In a floating wind farm setup, the tip-effect fluctuations are diminished in the wake merging region between two neighboring turbines. This region demonstrates a reduced level of intermittency compared to similar locations with a single wake flow. The center of the merging region reported one order of magnitude lower intermittency coefficient. A scale-universal non-analytical scaling exponent $\alpha = 1.3 \pm 0.14$ is found to be independent of turbulence intensity and turbine type.

4.5 Compounded Energy Gains in Collocated Wind Plants⁵

The streamwise velocity log profiles for the three simulated configurations are presented in Figure 4.36. The velocity is time averaged over a period of 30 min, which is the time scale

⁵The following results are adopted from, Kadum, H., Cal, R.B., Quigley, M., Cortina, G. and Calaf, M., 2020. Compounded energy gains in collocated wind plants: Energy balance quantification and wake morphology description. Renewable Energy.

used in temporal averaging of any quantity hereafter. A spatial averaging is also performed in the downstream and spanwise directions covering the entire numerical domain. The velocity corrected to account for the roughness length changes for each arrangement and is then normalized by the geostrophic velocity $u_g=9.5$. From this figure it can be seen that the standard wind plant SWP demonstrates a mean velocity that is higher than the CWP's below the bottom tip. The three profiles then collapse above the bottom tip. In order to be able to properly compare statistics between all cases, the effect of the difference in effective roughness on the normalized pressure gradient must be corrected first, similar to what was done in [Calaf et al., 2010].

Figure 4.36: Mean streamwise velocity profile horizontally averaged over the entire domain for the three cases studied normalized by the geostrophic velocity u_g . The dashed lines indicate the VAWT rotor top, HAWT bottom tip, hub height, and top tip from bottom to top, respectively.

The power harvested by each characteristic wind turbine is obtained by computing the

power of each turbine then averaging over the total number of turbines in the wind plant. Figure 4.37 presents the power extracted by a characteristic turbine for the standard wind plant, aligned collocated wind plant, and staggered collocated wind plant. The power extracted by a characteristic HAWT in the aligned plant configurations is roughly the same as the SWP. The power harvested by the staggered wind plant, however, is 5.8% lower than the other two cases. Taking the power extracted by the added VAWT clusters into account, Figure 4.37(c) shows that the combined harvested power of a HAWT and a VAWTs cluster is 3.5% higher and 2.5% lower than the standard plant in the aligned and staggered collocated arrangements, respectively. The increase or decrease percentages of any two quantities is calculated as $(X_1 - X_2)/X_1 \times 100$. Between the collocated plants, the aligned configuration harvests 6.2% more power than the staggered case. Even though the power produced by each VAWT cluster is higher in the staggered configuration, Figure 4.37(b), the total power extracted by a single HAWT and a single VAWT cluster combined is still larger in the aligned configuration. The mechanisms leading to the aforementioned findings are investigated by examining the mean flow statistics and wake recovery in section 4.5.1. A MKE budget analysis is presented in section 4.5.2 where the contribution and behavior of the terms in the MKE transport equation are described and compared for the configurations studied. The analysis in the aforementioned sections is conducted by establishing a control volume (box) around each horizontal axis wind turbine and evaluating the quantities of interest within this control volume. The box extends $(-D$ to $5.5D)$ in the streamwise direction, $(-1.25D$ to $1.25D)$ in the spanwise direction, and $(0$ to $2D)$ in the vertical direction [Cortina et al., 2016].

Figure 4.37: Power harvested per single isolated HAWT (a), VAWT cluster (b), and power harvested per an isolated HAWT and VAWTs cluster (c).

4.5.1 Mean flow statistics

Mean statistics for velocity and Reynolds shear stress are presented per single HAWT for the three cases investigated herein. Time averaging of a quantity is denoted with an overbar, $\overline{}$, while angular brackets $\langle \rangle$ are used to express spatial averaging. Figure 4.38 shows the streamwise mean velocity component $\overline{u}$ through consecutive slices upstream and downstream of the rotor. The slices represent the velocity in $z - y$ planes at several streamwise locations. Mean velocity $\overline{u}/u_g$ at $x/D = -0.1$ averaged over the rotor area, highlighted by black circles in Figure 4.38, is 0.52 on average for the standard plant layout. The aligned collocated configurations demonstrate increased velocity surrounding the swept area of the rotor when compared to the SWP layout, where the averaged velocity at $x/D = -0.1$ is 5.3. The staggered configuration shows a lower mean velocity. In the near wake, the velocity is recovered 90% at $x/D = 0.2$, the wake recovery declines after this location before recovering again. For the standard wind plant, the velocity reaches

90% recovery once again farther downstream at $x/D=1.7$. The SWP recovers 100% of its rotor velocity at $x/D=2.6$. The staggered CWP shows an improved wake recovery as it reaches 90% and 100% recovery at $x/D=1.4$ and $x/D=2.9$, respectively. On the contrary, the aligned configuration exhibits slower wake recovery than the SWP as it recovers 90% and 100% of its rotor velocity at $x/D=2$ and $x/D=3.5$. Figure 4.39 shows the third moment of downstream development of the velocity averaged over the rotor area as a representation of the portion of the flow that is interacting with the rotor to a successive turbine. The Figure highlights the signature of VAWT clusters on the HAWT wake observed as a sudden increase in velocity that extends over a distance of roughly two rotor diameters. The velocity profiles start with the SWP as the highest value, then once the flow passes the VAWT at $x/D = -0.37$, the velocity of aligned configuration becomes the highest. Similarly, at $x/D=3$ where the VAWT cluster is located in the staggered cases, the sudden increase in velocity is observed and it dissipates after two diameters at $x/D=5$.

In view of the above argument, the streamwise velocity development is examined in more detail in Figure 4.40. The Figure presents the ratio of mean streamwise velocity averaged over the rotor area $\bar{u}$. Spanwise profiles of the velocity ratio are shown in Figure 4.40(a). The velocity shown in these profiles is averaged in the vertical direction over the rotor area. The upstream location $x/D=-0.5$ reveals slower wake recovery in the CWP_{al} case whereas the SWP and CWP_{st} configurations have faster wake recovery. Beyond the aforementioned region, the difference between the aligned configuration and the other two cases shrinks due to the sudden velocity increase around that region. Farther downstream the difference increases again after the effect of the sudden velocity dissipates. The impact of VAWTs located to the side of the HAWT in the staggered case is apparent, where the velocity ratio profile is skewed towards the positive spanwise direction. The skewness in

Figure 4.38: Mean streamwise velocity normalized by the geostrophic velocity $\bar{u}/u_g$ for standard SWP, aligned CWP_{al} , and staggered CWP_{st} configurations. Slices are taken in $x/D=0.3$ increments from $x/D=-0.1$ to $x/D=5.5$. The red, black, and blue lines at the bottom of some slices indicate the location at which the velocity averaged over the rotor area $\langle \bar{u} \rangle_{yz}$ is near-wake 90%, far-wake 90%, and 100% of the velocity at the rotor.

Figure 4.39: Downstream development of the mean streamwise velocity cubed normalized by the geostrophic velocity $(\langle \bar{u} \rangle_r / u_g)^3$ for the standard SWP, aligned CWP_{al} , and staggered CWP_{st} configurations. The velocity is averaged over the rotor area (indicated by black circle in Figure 4.38). The vertical lines upstream and downstream the rotor indicate the location of the VAWTs cluster in the aligned and staggered cases, respectively.

the direction of the rotor rotation is a feature of the VAWT wake [Kadum et al., 2018]. The skewed, non-symmetric wake causes the staggered case to display a wake recovery rate that is faster than the SWP case on one side, $(+z/D)$, and slower on the other, $(-z/D)$. The effect of VAWTs vanishes in the near wake $x/D=0.5$ and the three configurations show similar velocity ratio profiles. A significant change in the velocity ratio behavior occurs at $x/D=3$, where the CWP_{st} case shows a sudden increase in wake recovery rate. This increase is due to the presence of VAWTs located at $x/D=3$ on either side of the HAWTs. Furthermore, the velocity deficit profile for CWP_{st} is skewed further downstream, see profiles at $x/D=5.5$. This is also related to the wake expansion associated with the VAWTs.

Figure 4.40: Mean streamwise velocity (a) lateral and (b) vertical profiles at various streamwise locations x/D normalized by the velocity at the rotor U_r . The lateral profiles are averaged in the vertical direction and the vertical profiles are averaged in the lateral direction. The dashed horizontal lines indicate the VAWT rotor top, HAWT bottom tip, hub height, and top tip from bottom to top, respectively.

The mean velocity vertical profiles averaged in the lateral direction and normalized by the mean rotor velocity U_r are presented in Figure 4.40(b). The Figure highlights the

relation between wake recovery rate of HAWT and the VAWTs presence. In the near wake, $x/D=0.5$ and $x/D=1$, the velocity ratio declines towards the center of the wake then grows moving vertically as it reaches a maximum value of $\langle \bar{u} \rangle / U_r \approx 1.3$. This trend is not observed in the far wake region as the wake has recovered and the velocity ratio is generally larger than 1 above the bottom tip. The profiles show that the locations with lower velocity ratio within the swept area of the rotor, $x/D=0.5$, 1, and 3, experience higher velocity ratios below the bottom tip. The opposite is true for locations $x/D=-0.5$, -0.25, and 5.5. This behavior is a consequence of the turbine wake employing the flow below the rotor to its recovery. At $x/D=-0.25$, the aligned configuration expresses the lowest mean velocity ratio within the rotor area amongst the studied cases as a consequence of VAWTs cluster presence at this location with its localized velocity deficit seen in the range of $y/D=0.08$ - 0.25. The effect of this presence persists up until $x/D=1$ perceived as streamwise velocity ratio equal to the other cases particularly within the swept area of the rotor caused by the added flow advected by the collocated turbines. This behavior then explains the enhanced performance of the wind turbine in the CWP_{st} case at $x/D=3$, exactly the position of the VAWTs. The VAWTs clusters increase the flow velocity below the HAWT bottom tip and results in an increase in the velocity in the wake core region behind the rotor. The 6.2% higher power produced by the aligned configuration compared to the staggered is a result of placing the vertical axis wind turbines closer to the HAWT. The clusters in the CWP_{al} and CWP_{st} cases are respectively placed $3d$ and $3D$ away from the HAWT in the streamwise direction. They are also placed $0D$ and $1.25D$ away from the HAWT center in the lateral direction. In addition, the location of the VAWTs in the aligned configuration is not only closer to the horizontal axis wind turbines, but also is upstream of them. This arrangement increases the incoming flow interacting with the turbine, see the upstream flow in Figure

4.39, resulting in larger power production.

To better understand the differences observed in the mean wake flow for the corresponding cases, the differences in momentum flux are investigated. For this purpose, Figure 4.41 provides a volumetric representation of $-\overline{u'v'}$ Reynolds shear stress. In SWP, Reynolds shear stress is directed downwards above the hub height. The area of this downwards shear stress expands in the spanwise direction further downstream. The upwards Reynolds shear stress degrades downstream and vanishes after $x/D=5$, coincident with the location found for the recovery in [Hamilton et al., 2012]. The CWP_{al} case exhibits heightened downwards and upwards Reynolds shear stress. The wake structure in the aligned case is similar to the wake structure of a standard plant SWP which is not the case for the staggered arrangement. In the CWP_{st} case, the HAWT wake and VAWTs cluster wake merge, thus leading to higher downwards Reynolds shear stress in the near wake compared to the SWP observed as larger regions of blue color between $x/D=1$ and $x/D=3$. On the other hand, the two wakes act independently in the CWP_{st} case while still interacting with each other resulting in a unique structure of the flow. The CWP_{st} wake is more confined due to the flow advected towards the center of the rotor from both sides by the neighboring VAWTs. The interaction of the VAWT wake with the HAWT wake causes the skewness observed in the velocity ratio profiles of the CWP_{st} wind plant but not in the aligned, see Figure 4.40(a). At and after $x/D=3$, an increase in the area of upwards Reynolds shear stress region is noticed in the staggered case caused by the VAWTs, indicated by two black lines at the bottom of slides bounding the region in Figure 4.41, though no increase in the magnitude is observed.

The vertical profiles of shear stress which include the Reynolds and dispersive contributions [Calaf et al., 2010] exhibit steep increases within the rotor area as shown in Figure

Figure 4.41: Resolved scales Reynolds shear stress $-\overline{u'v'}/u_g^2$ for SWP, CWP_{al} , and CWP_{st} wind plant configuration from left to right, respectively.

4.42. Above the top tip, the shear stress profiles converge gradually until reaching zero at $y/D=8$. The collocated plant configurations have higher shear stresses than the standard plant at the VAWT rotor region. The three configurations have similar shear stress with a marginal increase in the aligned case at the top tip as well as a marginal increase of the staggered case above the top tip. The aligned and staggered collocated arrangements have integrated shear stress over the entire domain height that is 3% and 4.5% higher than the SWP. This behavior is primarily caused by the Reynolds shear stress as the profiles are identical for both stresses. In addition to the top tip location, the collocated plants experience an additional Reynolds shear stress peak at the VAWT rotor top. The effect of the different arrangements is more apparent in the dispersive stress. The added VAWT clusters cause a 13.8% and 4% increase in the integrated dispersive stress over the entire domain height for the staggered and aligned cases, respectively, compared to the SWP. However, the dispersive stress values being three orders of magnitude smaller than the Reynolds shear stress, the increase in the shears stress of the collocated configurations is primarily caused by the changes in the Reynolds shear stress. The enhancement in verti-

Figure 4.42: Shear stress, Reynolds shears stress, and dispersive stress for three cases of a characteristic wind turbine normalized by the geostrophic velocity u_g^2 . The CV vertical dimension is $8D$ instead of $2D$ used in other computations to observe the profile convergence to zero. $\langle \overline{T_{xy}} \rangle$ is the Reynolds shear stress including the resolved scales $\langle \overline{u'v'} \rangle$ and the modeled sub grid scales $\langle \overline{\tau_{xy}} \rangle$. $\langle \overline{u''v''} \rangle$ is the dispersive stress. The horizontal dashed lines indicate the location of VAWT rotor top height, HAWT bottom tip, hub height, and top tip from bottom to top, respectively.

cal shear stress and streamwise velocity obtained by collocating clusters of VAWTs with HAWTs is placed further into perspective by examining how they reflect on the MKE entrainment. This aspect is discussed in detail in section 4.5.2 by studying the MKE budget of a characteristic HAWT turbine.

4.5.2 Mean kinetic energy

The mean kinetic energy MKE equation is described herein as,

$$0 = A + P + \mathcal{E} + F + \mathcal{P} + \mathcal{R}, \quad (4.2)$$

where A , P , $\mathcal{E}$, F , $\mathcal{P}$, and $\mathcal{R}$ correspond to the advection, transport due to pressure gradient, dissipation, flux, power extracted by the turbine, and the residual term, respectively. The

pressure and residual terms are neglected as their contribution to the MKE budget is found to be less than 2% combined. The remaining terms are given by;

$$A = -\overline{u_j} \frac{\partial \overline{K}}{\partial x_j}, \quad \mathcal{E} = \overline{\tau_{ij}} \frac{\partial \overline{u_i}}{\partial x_j}, \quad F = -\frac{\partial \overline{\tau_{ij}} \overline{u_i}}{\partial x_j}, \quad \mathcal{P} = \overline{\mathcal{F}_i} \overline{u_i}, \quad (4.3)$$

where $\overline{K} = \frac{1}{2}(\overline{u}^2 + \overline{v}^2 + \overline{w}^2)$ is the mean kinetic energy with $\overline{u}$, $\overline{v}$, and $\overline{w}$ being the stream-wise, vertical, and spanwise mean velocity components, respectively. Above, $\overline{\tau_{ij}}$ includes both the Reynolds shear stress $\overline{u'_i u'_j}$ and the sub grid shear stress $\overline{\tau_{ij}}$ whereas $\overline{\mathcal{F}_i}$ is the turbine body force. The vertical profiles of the MKE budget terms averaged horizontally in the x and y directions are shown in Figure 4.43. A positive quantity means it contributes to entraining MKE, while a negative quantity means it extracts MKE.

Figure 4.43: Mean kinetic energy budget for a characteristic turbine. The horizontal dashed lines indicate the location of VAWT mid rotor height, HAWT bottom tip, hub height, and top tip from bottom to top, respectively. K_i is the i^{th} term of the MKE budget including A , $\mathcal{E}$, F , and $\mathcal{P}$.

MKE flux

From the profiles, it can be observed that the wake recovery is primarily induced by the kinetic energy entrained from the flow above and below the rotor area represented by the kinetic energy flux $\overline{u'_i u'_j} \overline{u_i}$ as also noted in [Cal et al., 2010, Calaf et al., 2010]. The net kinetic energy flux is the difference between the upwards flux entrained from below the hub height and the flow entrained downwards from above [Kadum et al., 2019a]. A positive flux magnitude indicates the flux term is entraining MKE into the wake, while a negative flux magnitude indicates the flux term is extracting MKE away from the turbine wake. Below the HAWT bottom tip in the SWP arrangement, the flux acts as a sink of energy subtracting MKE from the turbine core wake with a relatively constant rate. Placing VAWTs alters the flux term within this region to a source of MKE with a sharply increasing gradient from about zero up to 3 times higher magnitude than the SWP configuration below the VAWT top. Above the VAWT rotor, the flux profile experiences a sharp gradient in magnitude and begins extracting MKE. However, the magnitude of the flux entraining MKE below the VAWT rotor is larger than the flux extracting MKE above it. As an overall result, the collocated wind plants flux term is a source of MKE below the bottom tip, while the SWP flux term is a sink. Increasing the drag below the horizontal wind turbines by adding the vertical axis wind turbines increases the net vertical kinetic energy flux especially in the areas closer to the VAWT location, where the drag caused by them is the highest. Similar to the VAWT rotor, the HAWT rotor causes a significant increase in the MKE flux that is directed into the wake, however, the flux does not experience the sharp gradient exhibited by the VAWT flux profiles. Above the HAWT top tip, the flux term converges to zero. The aligned collocated configuration shows an enhancement in the MKE flux compared to the SWP, while the opposite is true for the staggered case. The

CWP_{al} configuration retains the highest positive MKE flux below the hub height. The aligned case also shows a lower magnitude of negative flux extracting MKE directly below the bottom tip compared to the staggered configuration as a result of the VAWT placed close to the HAWT, causing their wakes to merge and be redirected into a MKE source faster than the CWP_{st} . The latter conclusion is validated by observing the flux profiles in Figure 4.43 between $y/D=0.3$ and $y/D=0.5$ and noting the different trends in which the two cases transfer from negative to positive flux magnitudes. The aligned case profile approaches zero almost linearly while the staggered case profile moves more gradually, thus showing a stronger compounded effect. The more homogeneous distribution of turbines in the CWP_{st} case is another reason for the gradual increase and decrease in flux values.

MKE advection

The behavior demonstrated by the flux term is also observed in the advection term profiles. The advection term profiles approach zero at the bottom tip before they increase again. The advection profiles of the collocated plants are similar within the HAWT rotor area and differ only below the bottom tip. The advection term acts as a source of MKE in the three arrangements. The collocated wind plants advect more MKE within the swept area of the rotor than the SWP. The CWP profiles behave differently below the bottom tip. It is apparent that the interaction between VAWt wake and the HAWT wake yields to each arrangement having a unique wake structure. The difference is apparent below the bottom tip due to the increased mean velocity, observed in Figure 4.39, associated with the added VAWTs. The difference, though less in magnitude, persists throughout the HAWT rotor up until $y/D=1.8$. The aligned configuration exhibits a sharp gradient of increasing and decreasing advection below the bottom tip, while the staggered demonstrate the more

gradual gradient similar to the flux term. This difference in the profile behavior suggests that the CWP_{al} contribute more to MKE through the advection term than the CWP_{st} .

MKE dissipation

The dissipation term peaks above the VAWT rotor for the collocated configurations while the standard arrangement shows a negligible dissipation within this region. Similarly, the top tip of the HAWT demonstrates another peak of dissipation term due to shear generated turbulence being the highest at these regions [Ali et al., 2019]. The variation in dissipation between the three configurations is mild within the rotor area, yet the aligned case dissipates more MKE than the other arrangements due to the increased roughness.

Integrated MKE budget

To better quantify the contribution of each term in the MKE transfer equation as well as compare the three configurations to each other, the integrated values over the control volume of the corresponding MKE terms is presented in Figure 4.44. Results indicate that the flux term is the primary contributor to MKE. This highlights the significance of increasing the turbulence momentum flux in optimizing wind plants performance. For the CWP_{al} and CWP_{st} configurations, the changes in Reynolds shear stresses leads to an increase of 4% and a decrease of 1.4% in the integrated flux terms, respectively, compared to the standard configuration. The aligned case experiences 4.6% more net MKE flux than the staggered case. This variation is a result of the sharper turn of the flux vertical profile, Figure 4.8, from being a sink of MKE to being a source below the bottom tip.

The second source of MKE is the advection term. The net advection of the standard wind plant is enhanced by a factor of 5.4% and 7.6% when collocated with VAWTs in an

aligned and staggered manner, respectively. In spite of the aligned configuration retaining the highest MKE flux, the staggered layout contribution to MKE via advection is the highest due to its faster wake recovery. The dominance of CWP_{st} advection term is observed in the vertical profiles above the VAWT rotor. It emphasizes the effect of staggering wind turbines in increasing the flow velocity and enhancing wake recovery which can be observed through the higher power harvested by a single VAWTs cluster when staggered compared to the aligned configuration, see Figure 4.38(b). However, the flux term being the leading term in the MKE budget, the aligned collocation configuration outperformed the staggered configuration in power harvested by a characteristic HAWT as well as the power harvested by HAWT and VAWT cluster combined. The net dissipation increases significantly in the CWP_s due to the added roughness, dissipating 1.4% and 1% more MKE than the SWP in the aligned and staggered cases, respectively. Overall, the highest dissipation is found in the CWP_{al} configuration suggesting energy loss related to the HAWT and VAWT wakes merging and higher roughness length.

Figure 4.44: Mean Kinetic energy budget integrated over the control volume. K_i is the i^{th} term of the MKE budget including A, $\mathcal{E}$, F, and $\mathcal{P}$.

4.5.3 Summary

The possible benefits of collocating VAWTs with HAWTs in a single wind plant are investigated using Large eddy simulations. Two collocation configurations are tested in which clusters of three VAWTs are placed either aligned or staggered with respect to HAWTs. Mean statistics and MKE budget of an isolated HAWT wake flow are conducted using control volume analysis.

The integrated MKE budget indicates that a single HAWT in the aligned and standard wind plants producing roughly the same power per single characteristic HAWT. On the other hand, the CWP_{st} is shown to negatively impact power harvested by a single HAWT. Taking the power produced by the added VAWT clusters into account, the CWP_{al} produced higher power per unit farm area than the SWP, 3.5% higher for this specific study. The study concludes that the power density can be improved once an optimal arrangement of collocated HAWT and VAWT is implemented. This finding urges a future study to identify the optimal arrangement, and the optimization should be primarily based on pinpointing the best placement to utilize the sudden velocity increase caused by the VAWT presence.

The MKE budget analysis reveals the leading role of vertical MKE flux increase in enhancing power production. The VAWT presence improves the mixing process of the wake flow by increasing the vertical Reynolds shear stress, but again once place in a preferred configuration. A significant increase in the dispersive stress is also observed in the collocated configurations due to their heterogeneous topography compared to a standard wind plant.

Placing the VAWTs cluster closer to and upstream of the HAWT causes the aligned collocation layout to out perform the staggered arrangement. The wakes of the two turbine types are close enough in the aligned configuration to merge into one wake with higher

turbulence shear stress and consequently higher MKE flux which is found to be the primary contributor to the MKE budget. Despite lower wake recovery rate experienced by the CWP_{al} , placing the VAWTs cluster upstream of the HAWT resulted in the latter profiting from higher inflow velocity compared to the other layouts. These findings suggest the possibility of improving the power density of a wind plant and power harvested by a single HAWT by placing VAWTs in optimized locations. The work highlights the importance of investigating more arrangements of collocated wind plants to arrive at possible arrangements that lead to power gain. It is also necessary to discuss the physics behind the changes observed in the collocated wind plants in terms of added roughness elements.

4.6 Implications of Spatial Heterogeneity in Forest Canopy Flows⁶

Control volume analysis for the flow within and above forest canopies is presented to examine canopy spatial heterogeneity implications of momentum transport. The goal is to develop a measure of spatial heterogeneity that accounts for various types of canopy variations and relate it to momentum transport terms. The relation between momentum transport terms and heterogeneity parameter is intended to be used in models to account for spatial variations in canopies

4.6.1 Geometric heterogeneity quantification: Lacunarity analysis

Lacunarity was initially proposed to measure the space filling nature of fractal patterns by Mandelbrot [1982]. The concept was subsequently expanded to quantify general spatial heterogeneity in various deterministic data sets [Allain and Cloitre, 1991, Kirkpatrick and

⁶The following results are adopted from a paper in preparation for submission to the journal of Boundary-Layer Meteorology.

Weishampel, 2005, Plotnick et al., 1996]. As lacunarity reveals significant length scales, it has found application in numerous fields including the characterization of heterogeneous landscapes [Frazer et al., 2005, Kirkpatrick and Weishampel, 2005, Plotnick et al., 1993]. Here, the lacunarity of each canopy arrangement is calculated via the gliding box algorithm developed by Plotnick et al. [1996]. In the gliding box approach, a box is marked around a small portion of the domain occupied by elements starting at the origin of the domain. Then the mass density s of elements occupying this box of size B is determined. The box is moved across the domain to measure the mass density at different location of the domain for the same box size. The box size is then increased in small increments to cover larger portions of the domain and the mass density at each box size is obtained using the same gliding box procedure. Additionally, the method proposed by Frazer et al. [2005] was employed to reduce mass density calculation time for each box. These mass density and box size results are then transformed into a probability distribution $Q(s, B)$ by dividing by the total number of boxes. The Lacunarity is then defined as the ratio of distribution variance to its mean and is described as;

$$\text{Lacunarity}(B) = \frac{\sum s^2 Q(s, B)}{(\sum s Q(s, B))^2} = \frac{s'^2(B)}{\bar{s}^2(B)} + 1, \quad (4.4)$$

where $\bar{s}$ represents the mean mass density and s' is the deviation from that mean.

Lacunarity profiles against box size are plotted to quantify how heterogeneous the domain is at each scale. Figure 4.45 shows the Lacunarity profiles for the forest canopy geometries tested in this study. Results demonstrate that for scales smaller than the tree crown diameter (indicated by a vertical dashed line), the profiles collapse for all cases. This is expected as the canopy arrangements have identical tree geometry as well as a

uniform tree distribution. The differences between the study cases occur at larger scales represented by the gaps and patches. At scales larger than the crown diameter, the infinite canopy case R_∞ asymptotes because the canopy geometry is uniform and no changes happen when increasing the box size. The arrangements with larger gap sizes demonstrate additional curvature after the crown size scale. Case p_2g_4 has the lowest tree density per pattern, hence it shows higher curvature peak and converges on lower lacunarity value of 0.17. In contrast, case p_2g_1 has the lowest peak and converges on higher lacunarity value of 0.34. The curves also extend over different box sizes. Shorter patterns require smaller box sizes to contain all the spatial heterogeneity in its geometry. Case p_2g_1 starts declining quicker and reaches convergence at box size $B=30$ cm, while the curve in case p_4g_4 declines slower and converges at box size $B=80$ cm. The box sizes required for each case to converge are the pattern length. This shows the accuracy of lacunarity at capturing the larger scale of spatial variations.

Lacunarity profiles are classically used to gain information about spatial heterogeneity by highlighting various scales, the peak of the curve, and/or the largest box size at which the lacunarity asymptotes similar to the information gained from Figure 4.45. Given that heterogeneity can occur at multiple scales and is assessed through a probability function, it is useful to quantify this information through a single, scalar value which can immediately indicate the heterogeneity of any canopy. Therefore, this proposed quantity encompasses all possible scales into a single quantity and opens the possibility of using this value to classify all types of heterogeneous surfaces.

To generalize the lacunarity representation, an analogy similar to the integral length scale taken in turbulent flows is made, where the area under the curve of normalized velocity correlations and length scales is integrated to determine the largest, most energetic

Figure 4.45: Lacunarity profiles used to evaluate the lacunarity parameter and integrated lacunarity scale L_c for the canopy study cases. the curves are evaluated over 3 pattern lengths for each case to reach convergence.

turbulent scale in a particular flow [Pope, 2000]. Lacunarity profiles in Figure 4.45 converge at different scales. These scales are indicated by black arrows and will be referred to as b . The scale b is equal to pattern length in the study cases and will differ for other types of heterogeneity. However, it will always represent the largest spatial heterogeneity in a particular setup. The lacunarity profiles will now be generalized by integrating the full extent of the forest. The scale b is used to indicate the upper limit for integrating the lacunarity curve to determine an integrated lacunarity, L_c as,

$$L_c = \int_0^b \text{Lacunarity } dx. \quad (4.5)$$

Unlike the integral length scale in turbulent flows, the integrated lacunarity, L_c , is not related to a physical flow process but rather to the geometrical properties of the particular forest. The integrated lacunarity is a dimensional quantity with units of length and can

therefore be non-dimensionalized. This then provides a dimensionless heterogeneity index to describe geometrical heterogeneity of a given canopy. The canopy height h_c is used to normalize the integrated lacunarity. The heterogeneity index Λ_g is expressed as,

$$\Lambda_g = \frac{L_c}{h_c}. \quad (4.6)$$

This index will be used to not only classify forest canopies based on their geometric properties, but beyond, will be tied to the flow characteristics as will be shown herein.

4.6.2 Mean velocity and Reynolds stresses

Mean flow statistics are presented for one sample canopy arrangement to describe the overall flow characteristics. Case p_2g_2 , with both gap and patch lengths of twice the canopy height, is shown in Figure 4.46 with an inflow velocity of $U_\infty 7.5 \text{ ms}^{-1}$. The measurement planes cover the gap length in heights below the canopy and cover a pattern length from half one patch through the gap and half a successive patch above the canopy. The measurement locations are chosen to cover distinct canopy layers. The trunk layer is measured at plane $y/h_c=0.4$, the foliage layer at $y/h_c=0.75$, the canopy top at $y/h_c=1.1$, and two planes for the mixing layer above the canopy at $y/h_c=1.25$ and 1.5 .

The mean streamwise velocity in the lower plane at $y/h_c = 0.4$ experience a recirculating zone as it has negative values. Planes $y/h_c = 1.1$ and $y/h_c = 1.25$ contain effects of tree tops indicated by regions with condensed contours in white colored lines. These region are more apparent in the vertical velocity component shown in Figure 4.46(b). Each tree top generates regions of high magnitude velocity. The flow approaching a tree is directed downwards into the gap between two tree crowns, then it is advected upwards once it passes the tree. The tree top signature is dissipated further above the canopy at $y/h_c=1.5$. In the

Figure 4.46: Streamwise velocity component U/U_∞ (a), vertical velocity component V/U_∞ (b), Reynolds shear stress $-\overline{u'v'}/U_\infty^2$ (c), and Reynolds stress $\overline{v'v'}/U_\infty^2$ (d) for case p_2g_2 and inflow velocity $U_\infty 7.5 \text{ ms}^{-1}$.

lower canopy, the flow leaving the first patch is directed upwards, then downwards moving towards the next patch. The same behavior is conserved in the upper canopy all the way to $y/h_c=1.5$ although the velocity magnitudes are lower.

Figure 4.46(c) shows the wall normal Reynolds shear stress. The Reynolds stress $-\overline{u'v'}/U_\infty^2$ is negative in the recirculating region. The recirculation region extends half the way across the gap at height $y/h_c=0.4$, and it is not present in higher vertical locations. The upper canopy experiences increasing shear stress even at 1.5 the canopy height. The vertical Reynolds stress $\overline{v'v'}/U_\infty^2$ in Figure 4.46(d) also experiences the tree top features

Figure 4.47: Streamwise velocity component U/U_∞ , vertical velocity component V/U_∞ , and Reynolds shear stress $-\overline{u'v'}/U_\infty^2$. Subfigures (a), (b), and (c) present profiles for case p_2g_2 at several streamwise locations within the gap. Subfigures (d), (e), and (f) present vertical profiles of the same quantities for the various canopy arrangements averaged over the gap distance. Inflow velocity $U_\infty 7.5 \text{ ms}^{-1}$.

and it shows a significant increase in value across the canopy layers. The mean velocity and Reynolds stress results show the dynamics experienced by the lower canopy reflect local canopy structure like a wake immediately behind the foliage and recirculation in the trunk layer, while the upper canopy shows tree tops features that are conserved even at $y/h_c=1.25$.

Downstream development of vertical profiles for the same quantities are presented in Figure 4.47 (a), (b), (c) for various x/G locations where G is the gap length. The mean streamwise velocity profiles show the vertical extent of the recirculation zone to the end of the trunk layer at $y/h_c=0.5$. Between the trunk layer and $y/h_c \approx 0.75$ there is a clear increase in velocity away from the foliage wake. The velocity requires more than four

canopy heights to fully recover the inflow velocity. The vertical velocity component in subfigure (b) is directed upwards in the first half of the gap, then downwards in the second. Profile $x/G=1$ shows an increase in the velocity of two times $x/G=0.8$ due to the flow accelerating down to the trunk layer. The vertical velocity component is reduced significantly above the canopy height. Reynolds shear stress profiles in subfigure (c) indicate that the stress starts converging to lower values after two canopy heights. The downstream location has its effect in the lower canopy then the profiles collapse together in the upper. In the lower canopy, the shear stress increases with streamwise location. Vertical profiles of the various canopy arrangements are compared in Figure 4.47 (d), (e), and (f). Case R_∞ is an infinitely long patch with no gaps. The measurements are taken behind the patch and only a few data points immediately behind the patch are averaged to obtain profiles for this case. This is done to minimize any downstream and wake recovery effects that make the profiles less representative of an infinite patch. Cases with smaller gaps experience stronger recirculation velocity in the trunk layer and slower streamwise velocity between the canopy height and $y/h_c=2.5$. The cases differ significantly in the vertical velocity component as can be seen from Figure 4.47(e) where cases R_∞ and p_2g_2 have downwards velocity that is at least two times as the other cases. The two cases also exhibit a sharp steep vertical gradient of this same velocity. Reynolds shear stress profiles in subfigure (f) don't vary significantly amongst the different cases below the canopy height although case p_4g_4 possesses the highest stress value at that part of the canopy. The cases differ in the upper canopy where denser canopies generate higher Reynolds shear stress. This difference is most pronounced between $y/h_c=1$ and $y/h_c=3$. Above $y/h_c=3$, cases with same or similar pattern converge together. Reynolds shear stress profile of the infinite case R_∞ and the smallest gap case p_2g_1 collapse together. case with the same gap to patch ratio,

namely $p_2 g_2$ and $p_4 g_4$, also collapse together. The previous results show the general mean flow statistic of the study cases. They provide basic but important information about the flow in each case offering explanatory points for the behaviour of more advance computations where the direct connection between the result and canopy structure might not be immediately obvious.

4.6.3 Control volume analysis

A control volume analysis is applied to the momentum equation terms. This analysis gives information about the flow globally rather than locally. It captures the effects experienced by the flow field as a consequence of the flow coming in contact with the forest canopy and thus factors, in this case spatial heterogeneity, can be evaluated and/or compared from all spatial locations. The advection and Reynolds shear stress gradient terms are calculated and the remaining terms including viscous, pressure gradient, and drag force are grouped into a residual term and treated together. The analysis is applied to the upper and lower portion of the forest canopy separately. Separating the control volumes is intended to investigate the two layers of the canopy individually. It is then beneficial to tie findings to the driving factors (patch length, gap length and Reynolds number) causing them. Given the shared surfaced at canopy height $y/h_c=1.1$, these two control volumes are connected and exchanges occurring there will become critical when evaluating heterogeneity; this will be demonstrated in the following subsections. The xz measurement planes allow for this kind of partitioning due to the planes collected at different heights some within the lower canopy and some in the upper. The momentum equation is written here once again as a reference of terms location in the equation as it affects the signs. The terms presented in the coming results are arranged as;

$$\underbrace{U_j \frac{\partial U_i}{\partial x_j}}_{\hat{A}} = - \underbrace{\frac{\partial \overline{u'_i u'_j}}{\partial x_j}}_{\hat{F}} - \underbrace{\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j^2} + F_i}_{\hat{R}}, \quad (4.7)$$

where the residual term $\hat{R}$ is obtained as $\hat{R} = \hat{A} - \hat{F}$.

Upper canopy

The upper canopy includes the flow above the canopy height. Three xz measurement planes taken at $y/h_c=1.1$, 1.25, and 1.5 are used to form the CV shown in Figure 4.48.

Figure 4.48: Control volume schematic for the upper canopy. The CV covers a pattern distance P in the streamwise direction and extends from $y/h_c=1.1$ to $y/h_c=1.5$ in the vertical direction. The lower canopy CV is similar to this schematic except it covers only the gap region in the streamwise direction and extends from $y/h_c=0.4$ to $y/h_c=1.1$ vertically.

Linear interpolation is used to evaluate the vertical locations in-between the three planes. The interpolated data is validated by comparing the vertical profiles of first and

second moment statistics to those obtained from the vertically resolved xy measurement plane. The profiles show good agreement. A sample result of the CV surface contours is presented for case p_2g_2 with inflow velocity $U_\infty 7.5 \text{ ms}^{-1}$. The remaining canopy arrangements will be presented as integrated values over surfaces and over the CV in subsequent results.

Figure 4.49 presents the momentum advection $\hat{A}$ and Reynolds stress gradient $\hat{F}$ entering and leaving the CV through its six surfaces. The advection in Figure 4.49(a) increases significantly moving vertically above the canopy in surfaces S_1 and S_2 . The advection entering the CV through S_1 is roughly equal to the advection leavening the CV through S_2 . The same is not true for the vertical advection in surfaces S_3 and S_4 because the surface immediately above the canopy S_3 shows a local effect of the trees manifesting as high vertical advection regions that are at least four times the magnitude of advection anywhere else on this surface or S_4 . The spanwise advection through surfaces S_5 and S_6 is an order of magnitude smaller than the vertical and streamwise advection components and is again balanced and roughly what is entering the CV through S_6 is leaving through S_5 .

The flux of momentum due to the Reynolds stresses in Figure 4.49(b) increases moving vertically in surfaces S_1 and S_2 similar to the advection term although a difference in magnitude is apparent between the two surfaces. This difference stems from the edge effect where the flow experience increased fluctuation when transitioning from a smoother section in the gap to an edge. The same effect is observed in the vertical stress gradient components.

The local tree effects in S_3 still exist in surface S_4 only closer to the edge between $x/P=0$ and $x/P=0.2$. The spanwise surfaces S_5 and S_6 contribute the least to stress gradient term and what is entering the CV through S_6 is roughly equivalent to what is leaving

Figure 4.49: Advection $\frac{\hat{A} h_c}{U_\infty^2}$ (a) Shear stress gradient $\frac{\hat{F} h_c}{U_\infty^2}$ (b) at the control volume surfaces for the upper canopy of case p_2g_2 .

through S_5 .

Lower canopy

The lower canopy represents the layer below the canopy height. The lower canopy CV covers the gap between two patches in the streamwise direction and extends from $y/h_c = 0.4$ to $y/h_c = 1.1$ vertically. Figure 4.50 shows the advection and Reynolds stress gradi-

ent term in the four dominant surfaces of the CV. The streamwise advection in the lower canopy behaves similarly to the upper canopy. Its magnitude increases vertically and what is entering the CV is roughly equivalent to what leaves the CV through surfaces S_1 and S_2 , accordingly. The vertical advection on the other hand is different from the upper canopy. The flow is advected towards the CV in both S_3 and S_4 specifically the second half of the gap. This result suggests the flow is being advected downward from the upper canopy when approaching a forest edge. The contours of S_5 and S_6 (perpendicular to the transverse direction), although included in the forthcoming analysis, are not shown here as their contribut

Figure 4.50: Advection $\frac{\hat{A} h_c}{U_\infty^2}$ (a) Shear stress gradient $\frac{\hat{F} h_c}{U_\infty^2}$ (b) at the control volume surfaces for the lower canopy of case p_2g_2 .

Reynolds stress gradient is presented in Figure 4.50(b). The flow in the lower canopy experiences significantly higher stress gradient than the upper canopy flow. The canopy foliage layer slows the flow down causing a region with higher Reynolds stresses that decrease in intensity farther away from the tree crown as shown in the lower $(\hat{F} h_c)/U_\infty^2$ values in surface S_2 . The lower and upper canopy flows show a consistent vertical Reynolds stress gradient throughout the canopy when considering the gap area. The magnitude are relatively higher farther from the canopy. It is worth noting that the $(\hat{F} h_c)/U_\infty^2$ values in S_3 are higher in the first half of the gap than the second highlighting again the necessity of considering the forest canopy as two separate layers before understanding how they influence each other.

The contributions of all six surfaces of the CV will be integrated and compared among the study cases to look at spatial heterogeneity impact the three component of momentum equation. The contributions will then be summed to obtain a volume integrate value for each term of the momentum equation per case. The volume integrated values are used to describe the global relationship between canopy arrangement and momentum transport. The relationship could improve existent atmospheric flow models to account for spatial heterogeneity effects might be neglected [Bou-Zeid et al., 2004].

4.6.4 Connecting geometric heterogeneity and momentum transport

The relation between canopy heterogeneity measured by the heterogeneity index Λ_g introduced in Section 4.6.1 and momentum transport terms is investigated herein. Figure 4.51 shows bar plots of the advection, Reynolds stress gradient, and residual; each integrated over the various surfaces of the upper canopy CV. The terms are normalized by the canopy height and inflow velocity by multiplying them be (h_c/U_∞^2) .

Figure 4.51(a) presents the surface integrated advection at each face of the CV. Each surface contains five bars that correspond to the five canopy arrangements investigated. The cases are organized on the x -axis in order of their increased heterogeneity index. The streamwise advection in S_1 increases with increased heterogeneity. The two most heterogeneous cases $\Lambda_g=2$ and 3 correspond to cases p_2g_4 and p_4g_4 , respectively. The two cases have similar gap size, but p_2g_4 has smaller patch size that introduce less drag causing it to have higher streamwise advection. The advection leaving the CV through surface S_2 is similar to that entering through surface S_4 in trend and magnitude. Surface S_3 of Figure 4.51(a) shows an increase in vertical advection magnitude with heterogeneity at the canopy top. It also shows a switch in the advection direction with larger gap sizes. The larger gaps cause upwards momentum advection near the canopy top. The effect of gap size becomes less apparent higher up in the canopy as S_4 shows an increase in advection with heterogeneity and all cases are advecting momentum down into the canopy.

Figure 4.51: Advection $\frac{\hat{A} h_c}{U_\infty^2}$ (a) Reynolds stress gradient $\frac{\hat{F} h_c}{U_\infty^2}$ (b) and residual $\frac{\hat{R} h_c}{U_\infty^2}$ (c) integrated over each surface for upper canopy plotted against geometric heterogeneity index Λ_g .

Figure 4.51(b) shows the Reynolds stress gradient. No significant dependence on the heterogeneity index is observed in the streamwise component as shown through surfaces S_1 and S_2 . The flux of momentum due to turbulence is relatively constant and is an order of magnitude smaller than that observed in the vertical direction (S_3 and S_4). In addition, the flux in the vertical direction in surface S_3 has a significant dependence on the hetero-

geneity index. The stress gradient $\hat{F}$ becomes more negative as the spatial heterogeneity is increased with p_4g_4 having the largest vertical flux - $4\times$ larger than R_∞ . The cause for this behavior is that an increase in momentum transport into the canopy when the heterogeneity is increased given that the flow is able to 'recover' over the larger patch and more intensely be driven downwards once the gap is encountered by the flow. This effect is present higher up in the canopy as can be seen from the identical behavior in surface S_4 , thus a bulk momentum of flow is observed to fill the void encountered by the gap.

The residual $\hat{R}$ is presented in Figure 4.51(c). The form drag which is present due to the flow interacting with the forest canopy is the leading term in the residual. Furthermore, when the heterogeneity index is small, $\Lambda_g < 1.6$, surfaces S_1 and S_2 are the leading contributors in the residual, when compared against the vertical 'lids'. For $\Lambda_g > 1.6$, the top surface is relatively lower in magnitude in comparison to surfaces S_1 through S_3 , thus pointing towards the pressure gradient in the streamwise direction and the drag imposed by the canopy taking the primary role at the canopy height. The streamwise component in S_1 and S_2 shows a heterogeneity dependence similar to the advection term, that is as Λ_g increases so does the residual. Case p_2g_4 with the smaller patch size experiences higher streamwise residual than case p_4g_4 . The residual in the upper canopy is most altered by spatial heterogeneity in the vertical direction. Surface S_4 is significantly smaller in magnitude than in S_3 .

The surface integrated terms of the momentum equation in the lower canopy are shown in Figure 4.52. The streamwise advection presented in Figure 4.52(a) increases with heterogeneity in surface S_1 , yet the effect of drag coefficient is observed in the sparse case p_2g_4 that shows the highest advection.

The advection shows similar trend leaving the CV through S_2 . A significant difference

Figure 4.52: Advection $\frac{\hat{A} h_c}{U_\infty^2}$ (a) Reynolds stress gradient $\frac{\hat{F} h_c}{U_\infty^2}$ (b) and residual $\frac{\hat{R} h_c}{U_\infty^2}$ (c) integrated over each surface for lower canopy plotted against geometric heterogeneity index Λ_g .

in the vertical advction components is noted in surface S_3 and S_4 . The advction is an order of magnitude lower than the horizontal component and its is almost negligible near the trunk layer in S_3 . Case p_4g_4 shows the downwards advction, which highlights the immediate effect of the flow passing larger patch than the other cases. The advction in the lower canopy is lower than that in the upper canopy due to the flow being confined

between two patches are under the effect of canopy drag in the lower part of the canopy.

Stress gradient in Figure 4.52(b) shows that the streamwise component in S_1 is lower than the the same component in S_2 which is a feature that did not occur in the upper canopy. The wall normal Reynolds shear stress component transports momentum upwards at the beginning of a gap, then switch direction closer to the end of the gap, see Figure 4.46. Those local differences in the lower canopy lead to its unique behavior compared to the upper canopy as well as amongst different canopy arrangements. The vertical component in S_3 and S_4 increase with heterogeneity. is shows a similar trend to the upper canopy, only an increase in magnitude is present in the latter.

Finally, the residual term is shown in Figure 4.52(c). The streamwise component is roughly similar in both S_1 and S_2 . The two surfaces reflect the local effects of canopy arrangement on the advection and stress gradient terms. The different between Cases p_2p_4 and p_4g_4 is reduced in surface S_4 as the flow recovers downstream the patches compensating for any variation between the cases caused by their patch sizes. The vertical component in surface S_3 follows an ascending trend with heterogeneity although cases p_2p_4 and p_4g_4 show mild difference. The top surface S_4 shows the most variations amongst the study cases. The residual values are lower in this surface compared to S_3 . This behavior is consistent between the upper and lower canopies.

4.6.5 Volume integrated momentum transport terms

The momentum equation terms are now integrated over the CV of each case for the upper and lower canopies, left and right column respectively. That is, the sum over all faces is undertaken as posed in Equations 2.41 and 2.42. The trend each of these terms exhibits with heterogeneity is presented in Figure 4.53. The advection, Reynolds stress gradient,

and residual are each divided by a reference value $\hat{A}_\infty$, $\hat{F}_\infty$, and $\hat{R}_\infty$ that correspond to the infinite canopy case R_∞ .

Figure 4.53(a) shows the advection increase with heterogeneity. The increase is significant and an steady increase in heterogeneity index from $\Lambda_g = 0.3$ to $\Lambda_g = 3$ leads to increasing the advection in the upper canopy by factor of 14. The advection term behavior in the lower canopy is different from that in the upper canopy. In the lower canopy, the edge at the end of the gap is considered a forward facing step, where the flow speeds up approaching the step [Zukoski, 1967]. Smaller gaps magnify this effect as the FFS region of impact accounts for larger portion of the gap. The FFS is responsible for the advection decreasing in value with increased Λ_g in the cases studied as the heterogeneity is introduced more or less by larger gaps. Another difference between the upper and lower canopies in terms of momentum advection is advection direction dependency on the forest density. Case p_2g_4 is the most sparse arrangement and it has the lowest patch to gap ratio and consequently lower drag coefficient, see Table 3.1. Studies have shown that below a certain value of LAI (which is directly related to drag), the flow exiting a forest patch does not experience a recirculation zone that usually occur with higher LAIs [Cassiani et al., 2008]. The recirculation zone creates a backwards streamwise flow which makes its occurrence important in determining the direction of advection term.

What is important to point out here is the fact that heterogeneity in lower canopy has much lower impact on the advection values than in the upper canopy, keeping in mind that quantities in the lower canopy are normalized by p_2g_1 as a reference case instead of R_∞ which causes the values to be even smaller. Even though the canopy spatial heterogeneity has less impact within the canopy itself and its effects is sometimes overruled by local factors like FFS and recirculating zone, its influence on the upper canopy flow is significant

Figure 4.53: Advection $\frac{\hat{A} h_c}{U_\infty^2}$ (a) Reynolds stress gradient $\frac{\hat{F} h_c}{U_\infty^2}$ (b) and residual $\frac{\hat{R} h_c}{U_\infty^2}$ (c) integrated over the CV for upper and lower canopies. The terms are divided by a reference value $\hat{A}_\infty$, $\hat{F}_\infty$, and $\hat{R}_\infty$ that is obtained from the reference canopy arrangement case R_∞ . Arrangement $p2g1$ is considered as the reference case for the lower canopy.

and closely related. The advection- Λ_g profile shows a relationship that can be beneficial to numerical weather prediction models and atmospheric sciences since the models are usually based on assumptions that neglects the advection term. The relationship achieved herein can be factored into those models to account for spatial heterogeneity in forest canopies and possibly other canopies and terrains.

Reynolds stress gradient $\hat{F}$ is presented in Figure 4.53(b). The results show increasing Reynolds stress gradient values with higher Λ_g . An asymptotic behavior at the higher heterogeneity values is observed. The heterogeneity index increase from $\Lambda_g = 0.3$ to $\Lambda_g = 3$ causes a growth in the Reynolds stress gradient by a factor of 3.6 in the upper canopy. The stress gradient in the lower canopy responds to heterogeneity in similar manner to the upper canopy and with the same order of magnitude. This similarity suggests turbulence transport occurring as one process across the canopy layers. canopies with gaps allow more of the upper flow to penetrate through the lower canopy creating turbulence exchange and mixing between the layers. Across layers momentum exchange has implication on forest growth through pollen dispersal and vapor and CO_2 cycles. It also shows that the canopy structure can alter the interaction between the canopy layer and ABL.

The residual term is shown in Figure 4.53(c). One can immediately see the high increase with heterogeneity as well as the similarity of this profile to the advection term profile both in the upper and lower canopy. The advection and residual terms are mostly affected by heterogeneity in the upper canopy, the lower canopy response is mild in comparison. The case is different for the stress term where it is altered on the same order both in the upper and lower canopies.

4.6.6 Flow heterogeneity and Reynolds number dependence

The heterogeneity index Λ_g is able to capture spatial variations in canopies and its results are consistent with CV analysis of momentum equation. Here, heterogeneity that is caused by the flow itself is investigated. Recent studies reported Reynolds number dependence in the dispersive stresses caused by spatial heterogeneity. Dispersive stress is a quantity that stems from spatially variations. Margairaz et al. [2020] noted that in spa-

tially heterogeneous distribution of thermal patches, the dispersive stress decreased with increasing geostrophic wind intensity. Figure 4.54 presents the dispersive stress fraction for case p_2g_2 . The dispersive stress fraction is the ratio of dispersive stress to Reynolds shear stress. The dispersive stress is computed as;

$$\overline{u''v''} = UV - (\langle U \rangle_{xz} \langle V \rangle_{xz}). \quad (4.8)$$

The xy measurement plane is used for this computation, so the spatial averaging of stream-wise and vertical velocity in the previous equation is done only in the streamwise direction. The value is then integrated in the vertical direction and divide by the integrated Reynolds shear stress value.

Figure 4.54 (a) compare dispersive stress fraction between different cases. In the lower canopy the dispersive stress contribute up to 13% of the Reynolds shear stress. The lower heterogeneity case p_2g_1 has the lowest stress fraction. This is not the only deciding factor, however. The larger impact region of FFS in case p_2g_2 leads to higher dispersive stress fraction in that layer. The larger gap cases have comparable fraction value, but case p_2g_4 shows negative dispersive stress near the floor. The dispersive stress effect above the canopy is mild. The results in Figure 4.54 (b) coincides with Margairaz et al. [2020] findings where the dispersive stress fraction decreased with increasing inflow speed. An interesting observation to make here is that the dispersive stress fraction dependence on Reynolds number is less pronounce at higher inflow velocities. A 1 ms^{-1} increase in the inflow velocity from 1 ms^{-1} to 2 ms^{-1} leads to 32% decrease in the dispersive stress fraction, while at higher speeds only 20% decrease is observed when increasing the velocity by 2.5 ms^{-1} from 5 ms^{-1} to 7.5 ms^{-1} . This observation will prove to be of significance in

Figure 4.54: Vertical profiles of dispersive stress fraction for various cases (a) and Integrated dispersive stress fraction evaluated at inflow velocities of 1, 2, 5, 7.5, and 10 ms⁻¹ for case p_2g_2 (b). The quantities are obtained using the xy measurement plane that extends through the gap in the streamwise direction and from 0 to $\approx 4h_c$ in the vertical direction.

the next step of this work.

These results motivated the work to further quantify heterogeneity by proposing a heterogeneity parameter that takes into account not only the geometrical heterogeneity effects, but also flow heterogeneity. The goal is approached by hypothesizing that flow heterogeneity is manifested as a balance between the mean flow advection and the turbulent mixing in which a scaling parameter is picked to represent each of these two factors. Similar analogy has been used before to describe added roughness effects. Yang and Meneveau

[2017] described the change in roughness elements distribution as a change in "sheltering" area as in larger elements shelters smaller ones. The sheltering area is an area of turbulence mixing that was found to increase and decrease with changing mean streamwise flow. The authors proposed a variable which they called α that is the ratio between the mean streamwise velocity at some roughness height to the friction velocity. Monin and Obukhov [1954] derived an expression in which the mean flow velocity relates to the friction velocity through a non-dimensional parameter of the substrate properties like the drag coefficient. This same ratio was also shown to be directly related to Reynolds number. Barenblatt et al. [1997] reported a linear relationship between this ratio and $\ln(\text{Re})$. The ratio increased with Reynolds number, but the increase rate becomes smaller with higher Reynolds number. This behavior aligns with the relation between dispersive stress fraction and Reynolds number discussed in Figure 4.54(b) and it serves as a link between flow heterogeneity and ratio of mean flow to turbulence mixing. On those grounds, the ratio between the mean flow advection and turbulence mixing is chosen as a measure of flow heterogeneity, where the streamwise mean inflow velocity and the friction velocity are used as velocity scales for flow advection and turbulence mixing accordingly. The inverse of this ratio is referred to as Λ_f and it is described as;

$$\Lambda_f = \frac{u_\star}{U_\infty}, \quad u_\star = \sqrt{-\overline{u'v'}_{h_c}}. \quad (4.9)$$

The validity of the proposed flow heterogeneity parameter Λ_f is tested in Figure 4.55. The friction velocity is evaluated at canopy height. The closest height to the canopy $y/h_c=1.1$ is used in the current computations.

The figure includes results for various canopy arrangements as well as various inflow velocities. The cases with inflow velocity 7.5 ms^{-1} are the same cases plotted in previous

Figure 4.55: Advection $\frac{\hat{A} h_c}{U_\infty^2}$ (a) Reynolds stress gradient $\frac{\hat{F} h_c}{U_\infty^2}$ (b) and residual $\frac{\hat{R} h_c}{U_\infty^2}$ (c) integrated over the CV for upper canopy and plotted against the flow heterogeneity parameter Λ_f . The terms are divided by a reference value $\hat{A}_\infty$, $\hat{F}_\infty$, and $\hat{R}_\infty$ that is obtained from the reference canopy arrangement case R_∞ .

figures with the geometrical heterogeneity index Λ_g . For the same canopy arrangement, increased inflow velocity leads to decreased heterogeneity as can be seen by looking at points $p2g2_{u5}$, $p2g2_{u7.5}$, $p2g2_{u10}$, for example. The cases compiled together in this single plot exhibit a trend that can be approximated to a power law behavior. The residual term follows similar trend to the advection.

The flow heterogeneity parameter relates directly to the stress gradient changes that

are induced by geometrical variation of the canopy. The canopy arrangements with same inflow velocity exhibit an ascending trend when plotted against Λ_f . That is not the case when considering cases with similar canopy arrangement, but different inflow wind speed. The difference in the terms response to the flow heterogeneity parameter is attributed to the fact that the friction velocity is computed from the shear stress term hence they are positively correlated, while the advection and drag relate to the mean flow velocity.

The results demonstrate that the flow heterogeneity parameter proposed herein can indeed capture heterogeneity whether it is caused by geometry or Reynolds number. That is not to say that the geometrical heterogeneity index is unnecessary. The heterogeneity index and its profiles with momentum equation terms, can evaluate those terms without any flow quantities measurements needed. This parameter is relatively practical. The relation between Λ_g and Λ_f shown in figure 4.56 can be beneficial in evaluating the mean flow velocity to friction velocity ratio immediately from the geometry index. The profiles and fit functions found here correspond to limited type of spatial heterogeneity which is stream-wise spacing. In real forests and other terrains the heterogeneity comes from different canopy elements heights, density, and distributions. The current results and relationships need to be further generalized by including cases of all heterogeneity types and several inflow wind speeds.

It is possible to combine the heterogeneity parameters in one factor that accounts for flow and spatial variations. A heterogeneity parameter Λ is proposed as;

$$\Lambda = \Lambda_f \Lambda_g = \frac{u_\star}{U_\infty} \frac{L_c}{h_c}. \quad (4.10)$$

Figure 4.57 shows the momentum equation terms profiles with the heterogeneity parameter

Figure 4.56: Geometry and flow parameters relationship.

Λ . Advection exhibits an increasing trend with heterogeneity. The various velocity cases show an increased advection with heterogeneity as well. This observation is also true for the residual term. However, the stress gradient term does not respond in a similar way. The term values increase with increased geometrical heterogeneity as can be seen by tracing the different case with the same inflow wind speed $R_\infty u_{7.5}$, $p2g1 u_{7.5}$, $p2g2 u_{7.5}$, $p2g4 u_{7.5}$, $p4g4 u_{7.5}$.

When considering different wind speeds for the same canopy arrangement, the stress term behaves in an opposite manner to advection and residual. The stress term increases with increased wind speed regardless of the heterogeneity measure being lower. That is because the stress gradient term responds positively to the friction velocity $u_\star$ as discussed earlier.

Figure 4.57: Advection $\frac{\hat{A} h_c}{U_\infty^2}$ (a) Reynolds stress gradient $\frac{\hat{F} h_c}{U_\infty^2}$ (b) and residual $\frac{\hat{R} h_c}{U_\infty^2}$ (c) integrated over the CV for upper canopy and plotted against the heterogeneity parameter Λ . The terms are divided by a reference value $\hat{A}_\infty$, $\hat{F}_\infty$, and $\hat{R}_\infty$ that is obtained from the reference canopy arrangement case R_∞ .

4.6.7 Summary

A geometrical heterogeneity index Λ_g is developed from lacunarity analysis to quantify this spatial heterogeneity. The heterogeneity index is then related to momentum transport equation terms using control volume analysis. The heterogeneity index is successful in capturing spatial heterogeneity as its increase coincides with momentum advection in-

crease. The advection term increases 14 times when the heterogeneity index increases from 0.3 to 3 in the upper canopy. The advection term in the lower canopy is not significantly influenced by spatial heterogeneity, while drag and the existence of a recirculation zone have a more pronounced effect. The stress gradient term increases by a factor of 3.5 in the upper canopy and is more affected by gap size as the cases with similar gap sizes have roughly the same magnitude of stress gradient term regardless of their heterogeneity index. The stress gradient term relationship with the heterogeneity index is similar in both upper and lower canopies.

The flow in the upper and lower canopies is shown to be different, yet related. The lower canopy flow is more localized in the sense that the momentum transport terms are affected by the local conditions of the canopy including the FFS effect and recirculation zone. Those differences in the lower canopy arrangement, density, and existence of the recirculation zone drive the changes in the upper canopy. The lower canopy showed less change in the magnitude of momentum transport terms with heterogeneity, but lead to much higher changes in the upper canopy.

Reynolds stress dependence is investigated and a flow based heterogeneity parameter Λ_f is also proposed. The parameter is a ratio between the inflow velocity and friction velocity at canopy height. The results obtained from Λ_f coincides with the results obtained from Λ_g for cases with similar inflow wind speed. The flow heterogeneity parameter is also able to detect heterogeneity caused by the inflow conditions as it differentiates between cases that have similar canopy arrangements but different inflow conditions. The advection term again exhibits a power law behavior with the flow heterogeneity parameter. The stress gradient term increases with increase spatial heterogeneity but decreases with increased inflow velocity. The residual term behaves similarly to the advection term. Both terms

increase with an increased flow heterogeneity parameter.

The relationship between heterogeneity parameters and momentum transport terms can serve as an addition to atmospheric flow models representing scales smaller than their grid size. The results showed a significant increase in those terms that should be taken into account when dealing with heterogeneous canopies. It also highlights the significant role of mean flow in momentum transport when spatial heterogeneity is present.

Chapter 5

Conclusions

Turbulent processes in wind plants and forest canopies are considered. Large canopies interact actively with the atmospheric boundary layer. The understanding of these interactions is key to employ in ecologically efficient manner. Canopy structure is primary factor in leading the dynamics of these interactions. Turbulent flux examination in a horizontal axis wind turbine array showed the wake of these turbines dominated by wind gusts entraining momentum from the atmospheric boundary layer above the canopy and from below the rotors. These gusts are carried by sweep and ejection turbulent events for at least four rotor diameters downstream each turbine. Altering the wind plant morphology by adding vertical axis wind turbine clusters amongst the horizontal axis wind turbines modifies the wake flow structure depending on the spatial distribution of the turbines. Some arrangements lead to a wake structure similar to conventional wind plants, while others lead to a combination of a skewed vertical axis wind turbine wake and a horizontal axis wind turbine wake. The arrangement that resulted in a combine wake extracted more power. This knowledge about canopy morphology and canopy turbulence serves as a guide to optimizing wind plants layout in seeking higher power production as well as minimizing land occupancy of these plants. When offshore wind plants are considered as an option to maneuver land availability, the wakes of wind turbines in pitching motion in-

introduce additional scales to the flow that are half the rotor diameter in size. The wake flow possesses higher intermittency than the conventional wind plants and the intermittency increased further with highly turbulent flow. The intermittency introduced by pitch motion dissipates after five rotor diameters which means that the intermittency might not propagate from one turbine to another. The later finding is significant for floating wind plant design and further investigation is required to test its relevance in floating wind turbines experiencing motions in all six degrees of freedom as well as wave-turbine interactions.

A heterogeneity parameter is developed to measure the spatial variability of canopy composition. The parameter consisted of geometric and flow related portions that are related to canopy structure and inflow Reynolds number, respectively. The parameter is able to capture the heterogeneity effects in forest canopies, consisting of alternating patches and gaps in the streamwise direction. The heterogeneity parameter is then used to determine the influence of canopy heterogeneity on the flow above and within the canopy. Using control volume analysis of the momentum equation, the spatial heterogeneity is found to alter the momentum equation terms in both upper and lower canopies. The lower canopy experiences less changes in those terms values compared to the upper canopy and it is dominated by local canopy factors including forward facing step and recirculation zones. The upper canopy responds more actively and directly to heterogeneity. Momentum advection and residual terms increase significantly with increase heterogeneity parameter. An increase of 14 times in advection occurs in the upper canopy compared to homogeneous canopy arrangement. The increase displays power law behavior and fit equations of those behaviors are obtained.

The findings in this study have implications on determining canopy structure effects on turbulent processes. The connection between the two is advantages to canopy layer-

ABL interactions. The knowledge of these interactions serves in influencing momentum and energy entrainment in wind farms that lead to faster wake recovery and smaller land occupancy as a consequence. In forest canopies, this knowledge is important in ensuring forests sustainability through pollen dispersion and cycles of CO₂ and respiration. Weather forecasting accuracy can be further improved by factoring canopy morphology impact. The intermittency analysis has implications on the development of offshore wind farms that offer vast areas to exploit and higher wind speeds to harvest.

Chapter 6

Outlook

Offshore wind plants are great potential to wind energy production. The concept of floating turbines is relatively new compared to conventional on land wind plants and there are many research avenues to explore. Floating wind turbines are free to move in multiple directions experiencing roll, surge, heave, pitch, and yaw motions. In the current study, the impact of pitch motion on the flow behind a wind turbine is examined in terms of intermittency. There are ways to add to this work by considering other motions either individually or together. The pitch motion was emulated in this study by allowing the turbine to move back and forth on a gimbal support. A new research can investigate placing the turbines on an actual floating platform. These platforms allow incorporating the water wave-turbine interactions. Pitch-induced intermittency is shown to dissipate five rotor diameters downstream in the current investigation. This finding can be further tested in wind array setup as oppose to a single wind turbine.

As land availability remains a challenge in wind plant installations and production capacity, developing new wind plant layouts that increase power production per unit area is beneficial. Collocated wind plant arrangement proposed in this work opens new layout investigations. There is a room to expand on the topic by optimizing the collocation arrangements to arrive at a layout that extracts the most power. The VAWT clusters in the

staggered cases can be placed upstream of the HAWTs no farther than two rotor diameters. The same arrangements can be investigated in a staggered HAWT farm. A second approach to optimizing the collocation configurations is to look at vertical axis wind turbine size with respect to the horizontal axis wind turbine investigating a balance between a size that extracts more power while not causing blockage to the horizontal wind turbine inflow. The size of VAWT is changed in terms of height and diameter. These dimensions should be reported normalized by the HAWT dimensions, that way a ratio between the two turbines is determined and can be applied to farms with various HAWT sizes.

When spatial heterogeneity is present, canopy arrangements considered consist of identical trees that are aligned in spanwise and streamwise directions. Heterogeneity is introduced as gaps forming alternating patches and gaps in the streamwise direction. These canonical arrangements where the spatial extent of the heterogeneity in conveniently ordered represent an ideal test case to validate the proposed heterogeneity parameter. The heterogeneity parameter developed in the current study proved successful in measuring spatial variations. To further add to the current setup, the data can be collected up to heights covering the mixing layer which is roughly three canopy heights. The measurement planes can be collected closer to each other vertically for improved values when integrating the data for control volume analysis. Lower inflow velocities, as low as 1 ms^{-1} , should be considered as spatial heterogeneity is pronounced significantly more in lower Reynolds numbers. The velocities should be collected for all the study cases as they can be used to develop relationship between heterogeneity index Λ_g and flow heterogeneity parameter Λ_f for a range of velocities. The dependence of Λ_g - Λ_f relationship on Reynolds number can then be determined.

Canopy arrangements for future study can include patches consist of various sizes trees

as well as patches where the trees are distributed randomly. Changes on larger scale include testing different types of patch geometry. The patches can be finite in streamwise and spanwise directions. This arrangement creates a forest that is made of quadratic, circular, or cross-shaped patches. Then the patches aspect ratio can be manipulated to test wide range of spatial heterogeneity. These samples of heterogeneity can be tested and used together to determine a more general advection - heterogeneity relationship for atmospheric models. Furthermore, spatial heterogeneity implications can be investigated in terms of turbulent kinetic energy for its role in active transport in forest canopies that determine biological and ecological processes.

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