

École polytechnique de Louvain

Atmospheric boundary layer control for increased wind farm power density

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Abstract

This thesis is framed within the global context of ecological transition. The concept of ecological transition applied to energy necessitates the diversification and sustainability of electricity production solutions. Wind energy is one of these viable options. Over the next decades, wind turbines are set to play a pivotal role in the European energy mix as the continent strives to meet ambitious renewable energy targets and reduce dependence on fossil fuels. Vertical axis wind turbines present an effective solution, especially for deployment in wind farms.

In order to increase the overall power output density of a wind farm, this thesis investigates the use of turbines with pitched blades to control the atmospheric boundary layer and bring the high energy flow towards the wind farm level. This study uses numerical simulations where the turbines are modeled using actuator cylinders coupled with a Large Eddy Simulation code.

In this investigation, the ability of a vertical axis wind turbine to deflect its wake is studied. The latter is used in several wind farm setups to achieve an atmospheric boundary layer control.

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List of Symbols

Physical parameters

D	Rotor's diameter	[m]
H	Rotor's height	[m]
c	Blade's chord	[m]
ϕ	Blade pitch angle	[°]
ω	Rotational speed	$[\frac{rad}{s}]$
θ	Blade angular position	[°]
x	Streamwise direction	[m]
y	Vertical/Spanwise direction	[m]
z	Transverse direction	[m]
U_∞	Free stream velocity	[m/s]
u	Streamwise velocity	[m/s]
v	Vertical velocity	[m/s]
w	Transverse velocity	[m/s]
ρ	Fluid density	$[\frac{kg}{m^3}]$
q_0	Dynamic pressure $0.5\rho U_\infty^2$	[Pa]
ω_x	Streamwise vorticity	$[\frac{1}{s}]$
z_c	Wake center transverse coordinate	[m]

Dimensionless numbers

AR	Aspect ratio $\frac{H}{D}$	[-]
B	Blade number	[-]
σ	Rotor's solidity $\frac{Bc}{D}$	[-]
Re_c	Chord-based Reynolds number $\frac{Uc}{\nu}$	[-]
C_P	Power coefficient $\frac{P_{mec}}{0.5\rho U_\infty^3 HD}$	[-]
C_z	Lateral force coefficient $\frac{F_z}{0.5\rho U_\infty^2 HD}$	[-]
λ	Tip speed ratio $\frac{\omega R}{U_\infty}$	[-]
TSR	Tip speed ratio $\frac{\omega R}{U_\infty}$	[-]
$\hat{t}$	Dimensionless time $\frac{tU_\infty}{D}$	[-]
CFL	Courant–Friedrichs–Lewy number $\frac{\Delta t U}{\Delta x}$	[-]

Chapter 1

Introduction

1.1 Wind energy

In a world with increasing needs in energy but with a certain interest in limiting greenhouse gases emissions, development and optimization of sustainable energy sources tends to be one of the biggest challenges of the next decades.

If the manufacturing, installation and maintenance of wind turbine is not taken into account, wind energy is a zero carbon energy source. However, if those steps are considered in the life cycle analysis of the wind turbine, emissions per kWh are 11 gCO₂e/kWh for onshore wind turbines and 12 gCO₂e/kWh of offshore wind turbines. A more usual gas energy production emits approximately 490 gCO₂e/kWh [18]. The difference is more than noticeable.

Wind energy have however an inherently intermittent behavior. Indeed, wind turbines are entirely dependent on weather conditions. With large scale wind power integration, its intermittency poses serious impacts on power systems, such as system reserves, reliability and cost [12]. But according to IEA, wind is one of the predominant sources of power generation in the Net Zero Emissions by 2050 Scenario [1]. Wind power has a great potential, particularly in offshore locations where the winds are usually stronger than onshore ones.

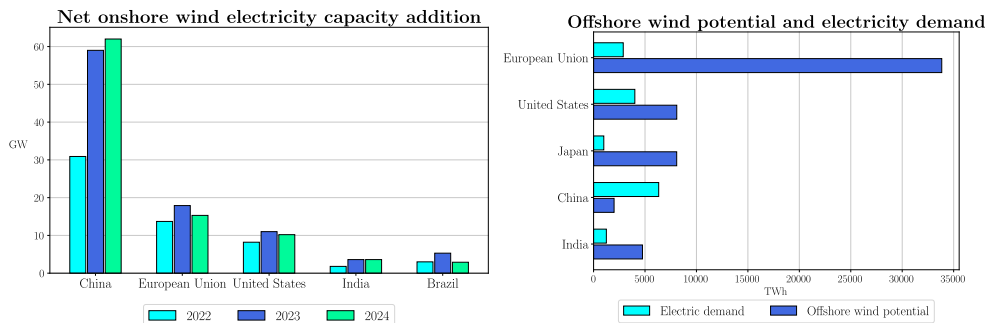


Figure 1.1: Net onshore wind electricity capacity addition by country or region, 2022-2024 (left), Offshore wind technical potential and electric demand, 2018 (right), [1]

1.2 Wind turbines

Wind energy can be harvested and turned into mechanical energy in the case of a windmill or into electricity through a generator for wind turbines. These turbines exist in many different configurations. It is however possible to separate them into 2 main categories: Horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). While the horizontal axis wind turbine is for the moment more widely used, the VAWT has several advantages that could be exploited.

Firstly, design of VAWT is relatively simpler than that of a HAWT. The low rotor's position of the VAWT makes it easier to do maintenance increasing thus its lifespan with respect to the HAWT. The lower gravity center makes the VAWT more suitable for floating marine applications [27]. The VAWT makes comparatively less noise than a HAWT. One of the greatest difference between the two configurations is that the VAWT can accommodate for winds coming from any directions and more turbulent ones [25]. Moreover, the distance for wake recovery is lower for a VAWT than for a HAWT [23].

On top of that, the theoretical limit of power extraction that a wind turbine can extract from the wind called the Betz's limit, is higher for a VAWT than for an HAWT. The Betz's limit for the latter is of $16/27 \approx 59.3\%$. For a VAWT this limit could be increased such that by crossing two times the air flow, turbine could extract up to 64% of the wind power [22].

The reason for which HAWTs are nowadays a part of the energy landscape is due to their higher efficiency, higher power per plant and lower levels of fatigue loading. The complex unsteady behavior of the VAWT due to the ubiquity of the dynamic stall phenomenon as well as the interactions between the blades and the wake made it unpopular [5].

VAWTs can be separated in two sub-categories, Savonius (drag-type turbine) and Darrieus (lift-type turbine). Savonius wind turbines harvest wind power through two or three scoops. A Savonius design suffers from the fact that only half of the turbine generates positive torque. The other side has to move against the flow thus creating negative torque. Savonius turbine, offers low efficiency but high reliability thanks to its simple design [2].

Darrieus wind turbines, on the other hand, use lift to generate power. It consists of several airfoils attached to the vertical shaft. Darrieus turbines can be sub-divided in three categories depending on their blade shapes. The simplest being the H-shaped with straight blades followed by the ϕ -shaped or parabolic rotor with curved blades, and finally, the helical rotor. The latter which shows better torque distribution over a rotation reducing the periodic loading amplitude thus increasing its lifetime [30]. The three distinct types of vertical axis wind turbines are depicted hereunder in figure (1.2).

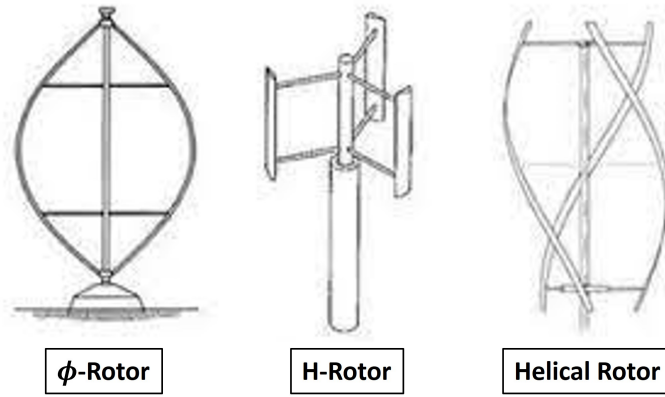


Figure 1.2: Darrieus wind turbines

1.3 Wind farms

In order to reduce the cost of the installation by taking the advantage of economies of scale, wind turbines are often clustered together. Those clusters, called wind farms, can be installed onshore as well as offshore. Offshore wind farms are more challenging to install but the wind is generally stronger and more uniform with less turbulence in those regions. The visual and sound impacts of the installation are also limited [8].

Wind farms offer advantages such as cost reduction and high power density. However, wake-rotor and wake-wake interactions can lead to power losses for individual turbines within the farm. The challenge lies in accurately modeling and controlling the wakes behind each turbine to minimize power losses or even enhance power production. In a wind farm, it is crucial to simulate turbine wakes and their interactions. The ability to predict turbine behavior is essential and can result in significant economic savings.

1.4 Blade pitch angle for wake steering

As onshore and offshore wind farms grow larger, reducing the spacing between turbines without significantly impacting their power output has become a crucial area of research and industrial focus [10]. Steering the wake can thus prove itself useful in the frame of a wind farm to enhance the overall power production of the installation.

A control over the wake trajectory can be achieved by pitching the blades of a vertical axis wind turbine. The introduction of a fixed blade pitch angle have for effect to modify the load distribution along the swept area and is the simplest way to deflect the wake [5][10]. This modified distribution can be such that the lateral resulting force is either increased or decreased depending of the blade pitch setting. Pitching the blades results thus in an introduction of lateral velocity by conservation of momentum [31].

The imposition of a fixed blade pitch angle causes a degradation in the capacity of the VAWT to extract power from the wind. However, in the case of a multiple turbine

installation, degrading the power output of the upstream wind turbine can prove itself beneficial for the downstream rotors [6] and for the overall production of the farm.

1.5 Objectives

This thesis is concerned with the objective of proving that in the context of an offshore wind farm composed with vertical axis wind turbines, VAWTs could be used as vortex generators. Combining the effect of several turbines working in given configurations of rotation's direction and blade pitch angle may allow atmospheric boundary layer to be controlled. Creating secondary flows above the wind farm to bring the high energy flow down to the level of the turbines could improve momentum recovery and increase overall wind farm power density.

Chapter 2

Numerical tools

2.1 Aerodynamic solver

Navier-Stokes equations, named after Claude-Louis Navier and George Gabriel Stokes are partial differential equations that describe mass, momentum and energy conservation in viscous Newtonian fluids. Under the assumption of incompressible flow, mass and momentum budgets are:

$$\nabla \cdot \mathbf{u} = 0 \quad (2.1.1)$$

$$\frac{D\mathbf{u}}{Dt} = -\nabla P + \nu \nabla^2 \mathbf{u} + f \quad (2.1.2)$$

$$\frac{D\boldsymbol{\omega}}{Dt} = (\boldsymbol{\omega} \cdot \nabla) \mathbf{u} + \nu \nabla^2 \boldsymbol{\omega} + \nabla \times f \quad (2.1.3)$$

Here, $\frac{D}{Dt}$ denotes the material derivative, $P = p/\rho$, and f represents the volumetric forces. Equations (2.1.2) and (2.1.3) are respectively the *velocity-pressure* and *vorticity-velocity* equivalent formulations of the momentum conservation equations.

In order to simulate the flow of a viscous Newtonian fluid, several methods exist. In the domain of CFD simulations, it is possible to identify three different kinds of methods. Direct numerical simulation (DNS), Large Eddy simulation (LES) and Reynolds averaged Navier-Stokes (RANS).

DNS is a heavy method that resolves Navier-Stokes equations in all temporal and spatial scales. Turbulence is directly computed without the use of any model. Direct numerical simulation provides the highest fidelity but requires a very fine grid in order to capture the smallest scales of turbulence thus leading to high computational costs.

LES method only resolve large-scales turbulence. The subgrid-scales (SGS) are filtered-out. However, the effects of these smaller scales on the resolved ones are simulated using a dissipation model. Adapted Navier-Stokes equations, expressed in a vorticity-velocity formulation are given below.

$$\frac{D\boldsymbol{\omega}}{Dt} = (\boldsymbol{\omega} \cdot \nabla)\mathbf{u} + \nu \nabla^2 \boldsymbol{\omega} + \nabla \times \mathbf{f} + \nabla \cdot \mathbf{T}^M \quad (2.1.4)$$

$$\mathbf{T}^M = \nu_{SGS}(\nabla \boldsymbol{\omega} - \nabla^T \boldsymbol{\omega}^s) \quad (2.1.5)$$

$\mathbf{T}^M$ is the subgrid-scale stress model and $\boldsymbol{\omega}^s$ represent the unresolved small-scales part of the vorticity field. ν_{SGS} is the eddy viscosity. More information can be found in [13]. This filtering will have for effect to greatly reduce the computational time.

Finally, RANS method as its name indicates, solve the Navier-Stokes equations by averaging the latter over time. This averaging process separates the flow variables into mean and fluctuating components.

$$u = \bar{u} + u' \quad (2.1.6)$$

The mean components represent the time-averaged behavior of the flow, while the fluctuating components represent the turbulent fluctuations. Turbulence models will have to be used to solve numerically the equations. RANS simulations computational costs are lower than CFD or LES while providing thrust-worthy results.

BigFlow, the code developed at UCLouvain and used in this work uses LES method with a in-house developed fourth order finite difference scheme. BigFlow solves the incompressible Navier-Stokes equations with a multi-grid solver developed by Duponcheel [9]. The time integration is performed by an explicit second-order Adams-Bashforth scheme.

2.2 Atmospheric boundary layer modeling

To better replicate physical conditions, it is necessary to simulate an Atmospheric Boundary Layer (ABL). The ABL turbulent inflow is generated by running a precursor simulation. In this simulation, the flow is driven by an imposed pressure gradient that compensate a given wall shear stress.

$$u_\tau^2 = -\frac{dP}{dx}H \quad (2.2.1)$$

Where H is a height of the domain. In order to avoid the important computational costs required to simulate properly the behavior of the velocity field near the wall, the friction velocity u_τ is obtained through a wall model based on the logarithmic law of the wall.

$$u_\tau = \frac{\kappa |\langle \mathbf{u} \rangle|}{\log\left(\frac{y}{y_0}\right)} \quad (2.2.2)$$

With κ the von Karman constant and y_0 , the roughness length that represents the roughness of the surface. The operator $\langle \cdot \rangle$ corresponds to a spatial averaging performed on a plane parallel to the wall, while the operator $|\cdot|$ denotes the norm of a vector. Using the mean friction velocity, the local shear stress is computed as:

$$\tau_w = \rho \frac{|\mathbf{u}|}{|\langle \mathbf{u} \rangle|} u_\tau^2 \quad (2.2.3)$$

The pressure-driven flow is then fed cyclically into a streamwise periodic domain. Once the ABL has converged under these conditions and reached a statistically steady state, the resulting velocity field is used as the inflow for the actual simulation where the turbines are placed. Both simulations then run in parallel.

2.3 Wind turbine model

The present work aims at studying the complex aerodynamics and wake of vertical axis wind turbines placed in a wind farm configuration. In order to simulate the influence of a VAWT inside a flow, several methods have been developed. In the frame of this work, an actuator cylinder model has been used to model every studied VAWT.

2.3.1 Actuator Cylinder Model (ACM)

The actuator cylinder model, developed by [14] extends the concepts of actuator disks, used for horizontal axis wind turbines, to the area of a cylinder. In an actuator cylinder model, the impact of the VAWT over the flow is modelled using the f term in the NS equations i.e., the external body forces per volume. The wind turbine is basically replaced by a surface made of an infinite number of blades that partially absorbs energy from the fluid causing the flow to slow down.

In practical terms, the ACM firstly interpolates the relative velocities at each grid points of the cylinder, then compute the forces acting on those points according to the polar of the airfoil composing the VAWT's blades [33]. Corrections such as dynamic stall and curvature effect are made during this step. Then the corrected forces are imposed on the flow.

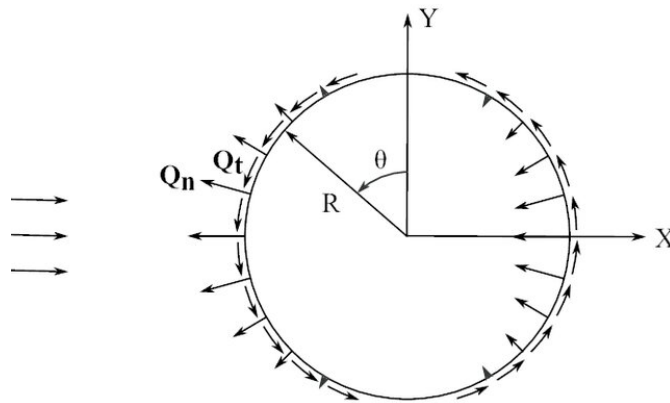


Figure 2.1: Actuator cylinder representation [33]

Other methods such as actuator disk, actuator lines, lifting lines or double multiple stream tube (DMST) can be used to model wind turbines in a flow.

2.3.2 Curvature correction

Curvature effect arise when an airfoil encounters curved streamlines. The angle of attack seen by the blade will vary along its chord. In the case of a vertical axis wind turbine, this effect is even more important when the solidity of the turbines is high [22].

In the frame of this work, a curvature correction has been implemented by pitching each blade inward by an angle of α_0 . This angle, which introduces a virtual camber to the airfoil, is computed using the same formula as in [22] [11].

$$\alpha_0 = \arctan\left(\frac{1 - \cos(\frac{\beta}{2})}{\sin(\frac{\beta}{2})}\right) \quad \text{with :} \quad \beta = 2 \arctan\left(\frac{c}{2R}\right) \quad (2.3.1)$$

2.3.3 Dynamic stall

Dynamic stall phenomenon occurs when the angle of attack of an airfoil undergoes rapid changes and exceeds the static stall angle of attack value [29]. Since the operation of a Darrieus wind turbine is directly related to the cyclical variation in incidence experienced by the blade, modelling this phenomenon is crucial if it is to correctly simulate the behaviour of a VAWT. This complex unsteady aerodynamics phenomenon will have for effect to delay the stall of the airfoil. This delayed stall provides significant increases in airfoil lift. Lift then quickly drops and the airfoil encounters a massive flow separation. The airfoil exhibits a significant hysteresis in force coefficients. Dynamic stall is highly related to the dimensionless tip speed ratio λ .

$$\lambda = \frac{\omega R}{U_\infty} \quad (2.3.2)$$

The dynamic stall effect becomes more pronounced at lower λ [21] due to the oscillation of the angle of attack between higher values.

The model used in this work is that of Leishman-Beddoes which has been implemented in a previous work at UCLouvain for actuator cylinder model by Adriaens B. [3]. However, certain constants of the model are found to be dependent on the Reynolds number and airfoil profile. The VAWT used in this work has been upscaled w.r.t the studied one in [3]. The involved constants have been computed again using the method described by Beaudet L. [22].

2.3.4 VAWT controller

The power produced by a wind turbine is highly dependent on the tip speed ratio λ . A turbine presents a maximal power production at a given λ_{opt} . In order to retrieve a maximal mechanical power from the wind turbine facing a variable velocity wind, a controller must be implemented to regulate the VAWT rotational velocity such that $\lambda \approx \lambda_{opt}$.

A controller will prove to be useful in a wind farm configuration in order to adequately regulate the speed of VAWTs subject to the effect of the wake from upstream turbines. The selected controller is a torque-based controller. It imposes a target torque Q_{Gen} at

the generator, and the difference between this imposed value and the aerodynamic torque Q_{Aero} results in variations in rotor's speed.

$$\frac{d\omega}{dt} = \frac{Q_{Aero} - Q_{Gen}}{I_{drivetrain}} \quad (2.3.3)$$

With $I_{drivetrain}$, the drivetrain inertia. In the code, the following equation solves for the angular velocity at the next time step using a simple first-order equation.

$$Q_{Aero}^n - Q_{Gen}^n = I_{drivetrain} \frac{\omega^{n+1} - \omega^n}{\Delta t} \quad (2.3.4)$$

At the time step $n + 1$, new aerodynamic and generator torques are computed based on the updated rotor speed ω^{n+1} . The control sequence is then applied again.

An expression for the torque at the generator has to be found. Power can be expressed in term of torque and rotational velocity through the expression of the power coefficient C_P :

$$P_m = Q_{Gen}\omega = \frac{1}{2}\rho U_\infty^3 S C_P \quad (2.3.5)$$

$$Q_{Gen} = \frac{1}{2}\rho \frac{U_\infty^3}{\omega} H D C_P \quad (2.3.6)$$

$$Q_{Gen} = \left(\rho H R^4 \frac{C_P}{\lambda^3} \right) \omega^2 \quad (2.3.7)$$

In a regime with the optimal tip speed ratio λ_{opt} , which maximizes power production at $C_{P,max}$, the torque at the generator is proportional to the square of the turbine's angular velocity.

$$Q_{Gen} = \underbrace{\left(\rho H R^4 \frac{C_{P,max}}{\lambda_{opt}^3} \right)}_{K=cst} \omega^2 \quad (2.3.8)$$

The constant K is linked to a given configuration of the wind turbine. In the following work, blade pitch angle will be introduced modifying the power curve and therefore the point $(\lambda_{opt} - C_{P,max})$. An adapted K will thus be computed for each turbine according to their blade pitch setting.

2.3.5 Striped wakes issues

Using the actuator cylinder method developed at UCLouvain in a uniform flow, the wake presents in some cases stripes structures which does not seem physical. Those lines also appears in other previous master thesis that used the actuator cylinder method such as [19] [30] [20] and [3].

The striped structures are mostly located on each side of the wake but propagate toward the hole mid-span wake in some conditions. The appearance of those stripes is favored by the pitch setting of the VAWT. They appear more clearly with a fixed inward pitch. The

number of those structures seems to increase with the magnitude of the pitch angle. The figure (2.2) hereunder presents the wake related to a fixed 5° inward pitch angle with 3 cross-sections of the streamwise velocity deficit. These cross-stream sections are measured at respectively 1, 2 and 3 diameters behind the VAWT. The stripes are also visible in the vertical direction.

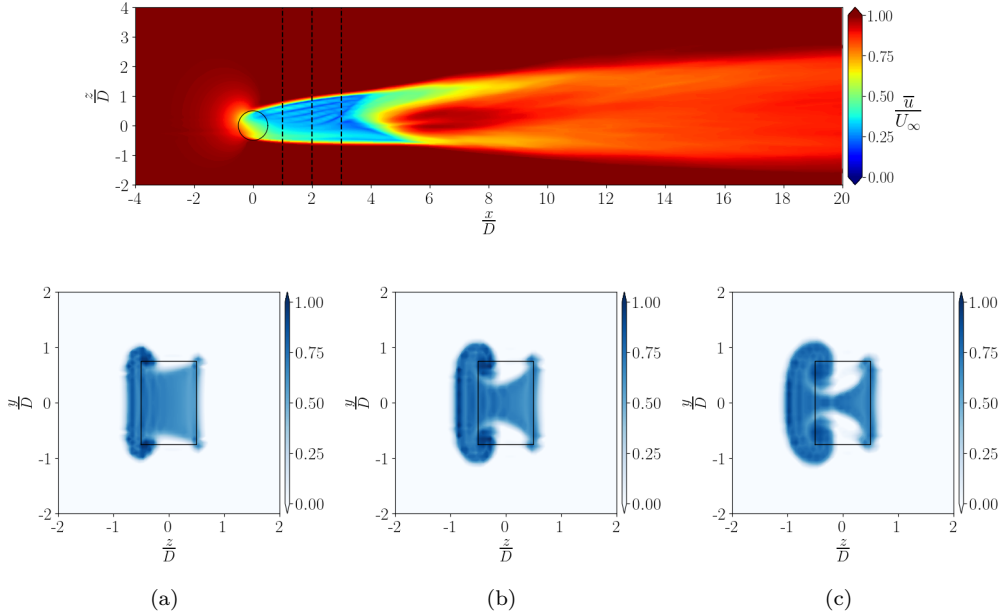


Figure 2.2: Time-averaged streamwise velocity at mid-span with pronounced stripes with fixed 5° inward pitch angle (top). Velocity deficit $1 - \frac{\bar{u}}{U_\infty}$ on cross-stream sections 1 (left), 2 (center), and 3 (right) diameters past the VAWT.

Some investigations were carried out by modifying the VAWT discretization, the order of the aerodynamic solver and especially on the mollification¹ to address this issue. The details of those investigations are included in the appendix (A).

The investigations show reduced stripes intensity in some situations. However, this smoothing caused the influence of the actuator cylinder to spread too much, resulting in lower quality results. In the frame of this TFE, the choice is made to keep using the original method since the overall behavior of the wake is consistent.

¹Distribution of the forces generated by the actuator cylinder upon the flow

Chapter 3

Single rotor wake dynamics

3.1 Introduction

When a flow passes through a wind turbine, the resulting flow behind the rotor is characterized by highly turbulent vortices and a considerable decrease in speed. This wake is then gradually re-energized through momentum transfer from the outside of the wake towards its center. A wind turbine placed in the wake of an upstream turbine will experience a reduction in the velocity of the incoming flow, which significantly decreases its power production. Since the maximum power available for harvest from a flow is proportional to the cube of the wind speed, even a small drop in wind speed can lead to a substantial reduction in power output. In a wind farm setting, wake deflection has been proven to be an effective method for increasing the power production of downstream turbines [4].

Modifying the blade pitch angle of a vertical wind turbine changes the load distribution over the rotor [5], [10]. Proper adjustment of the pitch angle can generate a significant lateral force. Understanding the behavior of the wake for a range of fixed blade pitch angles could help increase the overall power production of a wind farm through wake deflection.

In this chapter, analysis are made on a given vertical axis wind turbine over its capacity to generate lateral forces over the flow in order to deflect the wake while maintaining a substantial power output.

3.2 Wind turbine

The studied wind turbine is a H-rotor type VAWT scaled up to produce approximately the same amount of nominal power as the NREL 5MW. Dimensions, listed below, have been retrieved from the work of Collin C. and Moëns V. [30]. The VAWT is simulated using an actuator cylinder composed of 24 rings in the spanwise direction each one counting 90 azimuthal points evenly distributed.

Parameter	Value	Unit
Aspect ratio : AR	1.5	[-]
Height : H	138	[m]
Diameter : D	92	[m]
Chord : c	5.29	[m]
Blade number : B	3	[-]
Solidity : σ	0.1725	[-]
Airfoil	NACA0015	

Table 3.1: VAWT parameters

The local Reynolds number based on the chord Re_c experienced by the VAWT mostly varies with the azimuthal position, the angular velocity, and the spanwise position. The data used in this work are the lift and drag coefficients of a NACA0015 airfoil for a $Re_c = 10^7$ from Sandia Laboratories [28].

Several blade pitch angle configurations are studied, figure (3.1) presents a visualization of the inward/outward configurations. However, an ACM is used, no blades are actually moving. The figure only purpose is to give an idea of the blades configurations. The red and blue colors are respectively associated to inward and outward blade pitch angle while the black color is linked to a zero blade pitch. This color code will be kept during the entire chapter. An inward blade pitch angle ϕ is counted positive while a $\phi < 0$ refers to an outward setup. It is important to note that the blades are already pitched inward by an angle of $\alpha_0 = 1.65^\circ$ to add a fictive camber and thus count for the curvature effect.

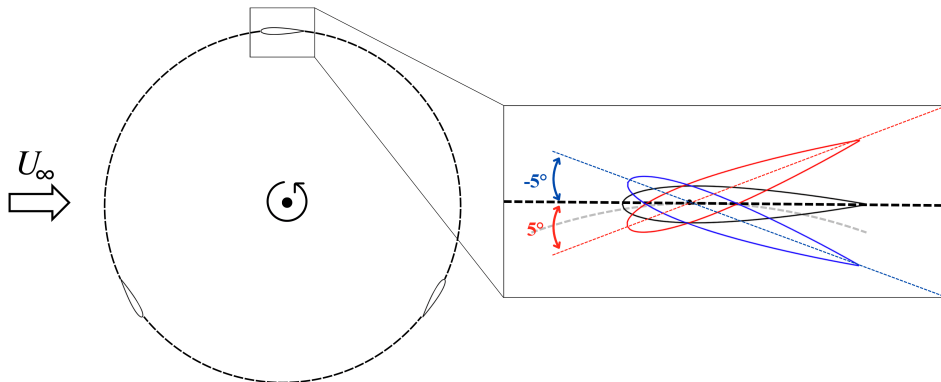


Figure 3.1: Blade pitch angle convention representation: No pitch angle P0 (black), inward configuration P5 (red), outward configuration P-5 (blue)

For each blade pitch configuration, the controller constant K is tuned according to the related $(\lambda_{opt} - C_{P,max})$. Figure (3.2a) presents the evolution of the power coefficient with respect to the tip speed ratio for every pitch configuration studied in this chapter. The figure (3.2b) shows the optimal conditions where the VAWT should be running.

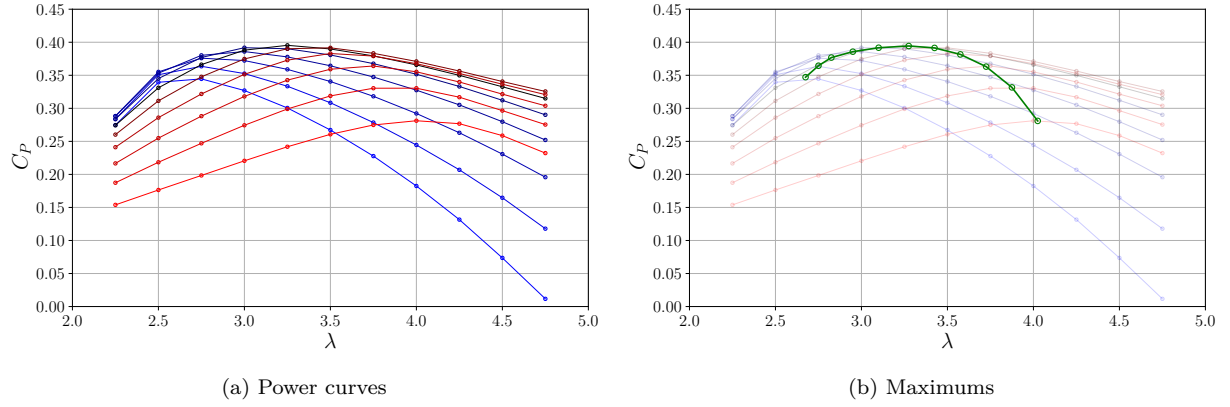


Figure 3.2: Power curves for every pitch angle in $[-5^\circ; 5^\circ]$ (left) The reddest curve is associated to 5° inward pitch while the bluest is related to 5° outward pitch. Associated maximums in green (right)

In the figure (3.2a), each point represents the power coefficient at steady state. Once the wake is developed, the power produced by the turbine tends to a constant value in a uniform wind or at least, slightly vary around it. When the standard deviation of the power remains within a given tolerance, the 'steady' power coefficient is considered to have reached this constant value.

These curves are generated by running simulations with the wind turbine and numerical setup described below. The rotational velocity and blade pitch angle are fixed to the desired values to obtain each point on the curves. The simulations are conducted for a dimensionless time of $\hat{t} = 10$, for at the end of which the power coefficients approaches their converged values.

The optimal values of the tip speed ratio and the corresponding controller constant K for each blade pitch setting are presented in the table below. A drivetrain's inertia $I_{drivetrain}$ of $50 \cdot 10^6 \text{ kg}\cdot\text{m}^2$ was used to determine the controller constant K following the methodology described in the previous chapter.

ϕ	P-5	P-4	P-3	P-2	P-1	P0	P1	P2	P3	P4	P5
λ_{opt}	2.65	2.72	2.80	2.92	3.06	3.23	3.38	3.53	3.68	3.82	3.97
$K (\cdot 10^6)$	14.3	13.8	13.2	11.8	10.3	8.8	7.7	6.6	5.5	4.5	3.4

Table 3.2: Optimal tip speed ratios and controller constants for each blade pitch setting.

3.3 Wake steering strategy

This section focuses on the ability of a vertical axis wind turbine to deflect the wake sideways. This deflection is achieved following the same method as [7]. A fixed blade pitch angle is imposed on each of the blades. The blade pitch angle does not vary along the span and is the same for every blade. The latter is fixed during the entire simulations.

3.3.1 Methodology

Turbine's configurations

10 configurations are evaluated beside of a reference one without blade pitch. The blades are pitched in 1° increments until 5° either inward or outward. Outward pitch settings are denoted P-X whereas inward settings are named PX, X being the pitch angle ϕ in degree. The configuration without any pitch angle is denoted P0.

Numerical setup

The vertical axis wind turbine is placed in a rectangular parallelepiped domain of dimensions $[24D \times 10D \times 10D]$ in streamwise, vertical and transverse directions respectively. The domain size is chosen to be sufficiently large to minimize the influence of the inflow and outflow conditions as well as to avoid blockage effect from the periodic boundary conditions explained further.

The inflow and outflow conditions are applied streamwise while slip conditions are applied over the bottom and top boundaries. Periodic conditions are imposed on both lateral sides.

In order to observe the effect of the blade pitch angle over the wind turbine as well as on behavior of the flow, the choice is made to study an uniform incoming flow with a free stream velocity $U_\infty = 11$ m/s. The wind turbine is placed 4 diameters downstream of the inflow and is centered with respect to the vertical and transverse directions. The mast of the turbine is not simulated. In the figure below as well as for the rest of the graphs in this work, conventions are taken such as the x-axis, y-axis and z-axis are respectively aligned with the streamwise, vertical and transverse directions.

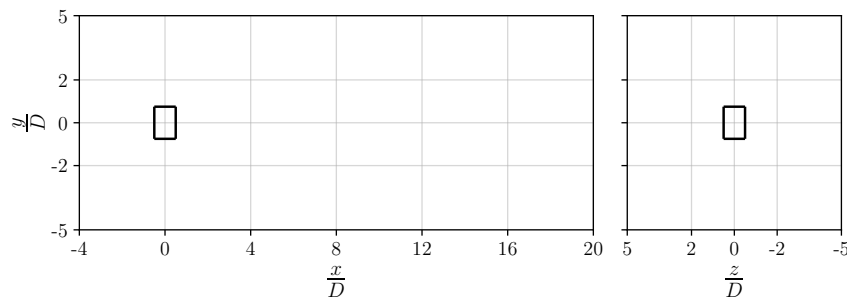


Figure 3.3: VAWT location visualisation, side view (left), front view (right), the inflow correspond to $x/D = -4$

The domain is meshed uniformly using 16 points per diameters. The resulting spatial increment is thus $\Delta x = 5.75$ m. A maximal time step is found by limiting the CFL number to 0.20 to avoid computational instabilities.

$$\Delta t = \frac{CFL_{max} \Delta x}{U_\infty} = 0.104 \quad (3.3.1)$$

A smaller time step of $\Delta t = 0.05$ s is used to limit instabilities in regions of higher local velocities and to obtain finer results. Simulations are performed over $\hat{t} = \frac{tU_\infty}{D} = 100$ dimensionless time in order to let the wakes develop which correspond to 16720 iterations for the chosen time step.

3.3.2 Diagnostics and performances

In this subsection, performances of each VAWT setting are evaluated with an emphasis over the ability to deflect the wake trajectory. The conventions used for the blade angular position θ as well as for the directions on normal and tangential forces are depicted on figure (3.4).

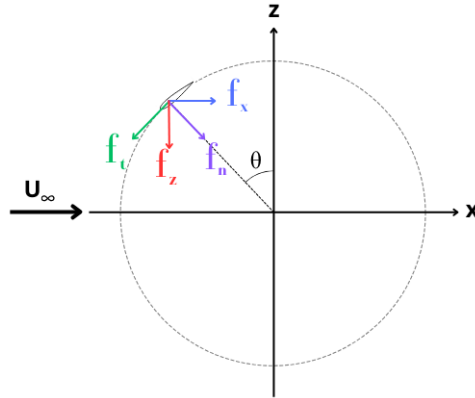


Figure 3.4: Conventions for angular position and local forces f_x, f_z, f_n, f_t acting on the cylinder

Figure (3.5) presents the profiles of angle of attack as well as the normal and tangential forces with respect to the azimuthal position for each one of the pitch configurations. The forces are made dimensionless with the chord c and the dynamic pressure $q_0 = \frac{1}{2}\rho U_\infty^2$

Those value are measured at mid-span and are averaged over 5 rotations of the turbine. Since the rotation speed varies with the blade pitch configuration due to the controller, each case must be analyzed independently of the others. However, general tendencies may be discerned.

The convention chosen is such that the normal force acting on the blade is taken to be positive when directed towards the center on the rotor, while the tangential force is defined positively pointing towards the leading edge see figure (3.4).

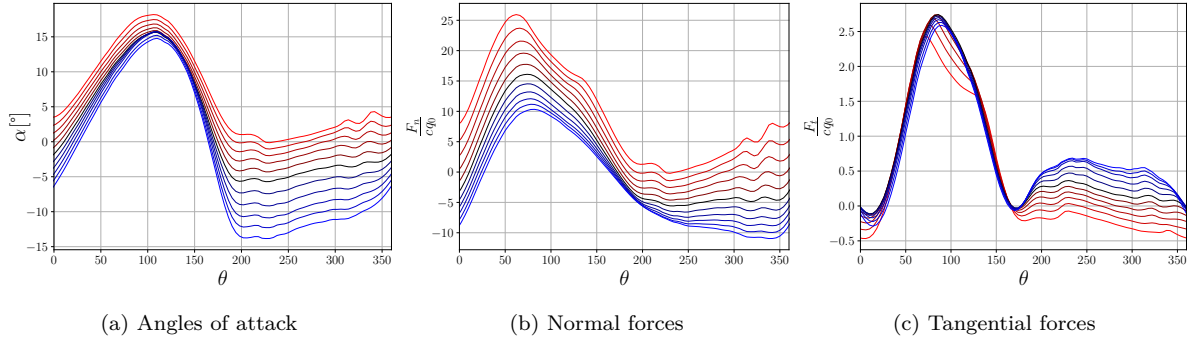


Figure 3.5: VAWT azimuthal time-averaged distribution of angle of attack and loads for every pitch angle $\phi \in [-5^\circ; 5^\circ]$ at mid-span. Inward pitch (red), Zero pitch (black), Outward pitch (blue)

Angles of attack

A positive angle of attack corresponds to a relative velocity coming from outside of the cylinder swept by the blades.

For every pitch configuration, the angle of attack shows a non-symmetrical distribution between upstream and downstream sides of the cylinder. This non-symmetrical distribution is due to the fact that the downstream part encounters a flow that already went through the upstream part. Small oscillations are also noticeable as the angle of attack slowly increases back to the $\alpha(\theta = 0)$ value. These oscillations might account for the increasingly prominent striped pattern as the pitch becomes more pronounced.

When a pitch angle is introduced, it can be observed that the angle of attack is essentially shifted by the pitch angle at $\theta = 0$. In the upstream part of the rotor i.e., $\theta \in [0^\circ, 180^\circ]$ the AoAs increase rapidly up to at least 15° . With pronounced inward blade pitch configurations, the angle of attack reaches higher values. In the downstream part of the rotor, the difference between each curves is more pronounced and α can reach impressively low values in the outward blade pitch cases.

Force coefficients

In general, positive values of $\frac{F_n}{cq_0}$ and $\frac{F_t}{cq_0}$ are observed in the upwind part of the rotor, whereas in the downwind part, the normal force is nearly always negative. The tangential force shows a second, yet smaller, positive bump.

Figure (3.5b) shows a wide distribution of the normal force with respect to the blade pitch angle. While the outward setups exhibit a $\frac{F_n}{cq_0}$ mostly centered around 0, the inward configurations progressively shift the normal force toward higher positive values.

A stalled region is observable around $\theta \approx 100^\circ$ as soon as the blade pitch angle exceeds 2° inward. This phenomenon has for impact to decrease the maximal normal and tangential forces in the upstream part of the turbine. The size of the stalled region increases with

the blade pitch angle and its effect is clearly visible on figure (3.5c).

Focusing on the lateral force, the normal and tangential forces per element (f_n, f_t) are calculated by BigFlow. The total lateral force is then determined by expressing f_n and f_t in the (x, y, z) coordinate frame (see figure (3.4)) and by summing the contributions of every element. The lateral force is then made dimensionless by dividing it by $\frac{1}{2}\rho U_\infty^2 HD$.

$$f_z = \sin(\theta)f_t + \cos(\theta)f_n \quad C_z = \frac{F_z}{0.5\rho U_\infty^2 HD} \quad (3.3.2)$$

For each blade pitch angle configuration, the C_z coefficient reflects the ability of the VAWT to deflect the wake. Lateral force coefficients are gathered for each blade pitch configuration in the table (3.3).

ϕ	P-5	P-4	P-3	P-2	P-1	P0	P1	P2	P3	P4	P5
C_z	-0.097	-0.053	-0.010	0.035	0.081	0.128	0.178	0.229	0.280	0.328	0.370

Table 3.3: Lateral force coefficients for each pitch configuration

For the sake of completion, the respective contributions of the normal and tangential forces are presented on the figure (3.6) for each configuration. The tangential part stays roughly constant or increases for high inward pitch whereas the normal force contribution behaves nearly linearly with the blade pitch angle. The latter reflects the wide distribution of $\frac{F_n}{cq_0}$ with ϕ observed earlier.

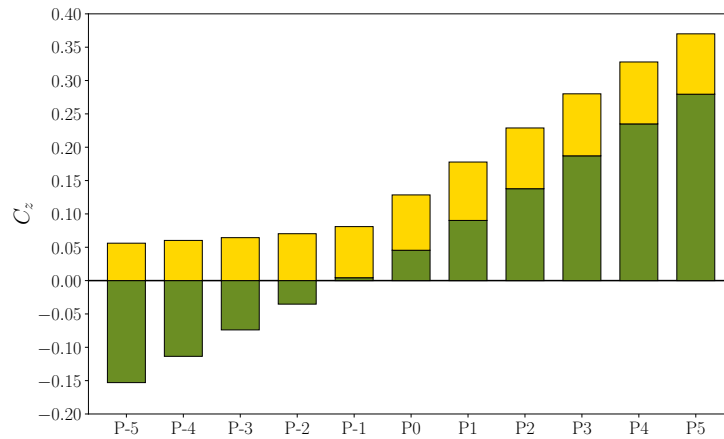
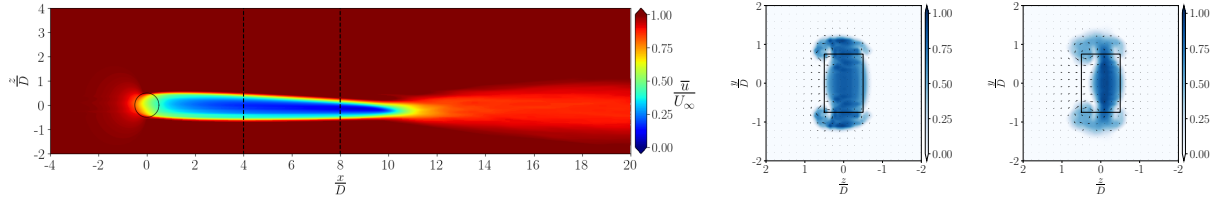
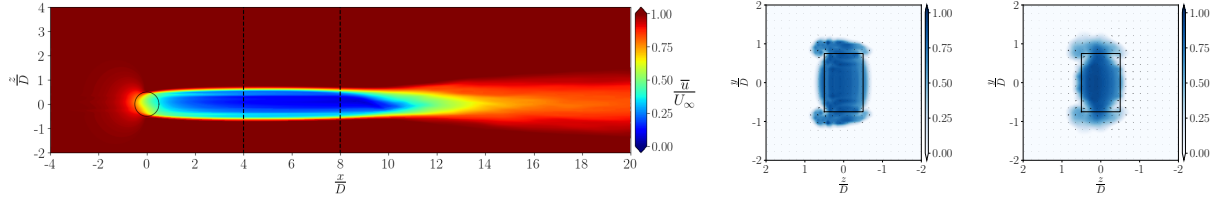
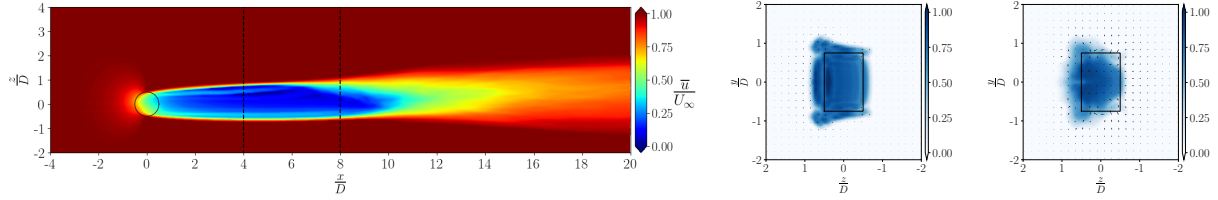
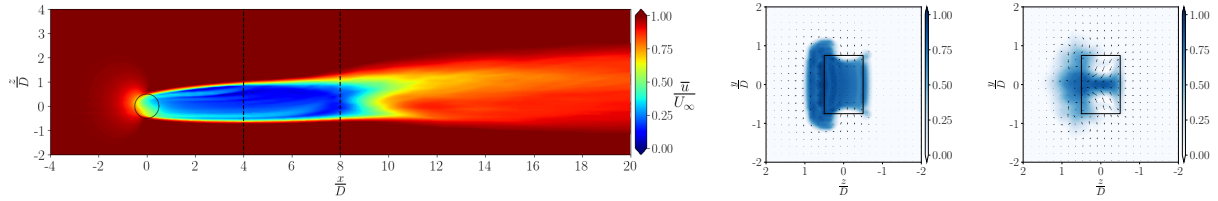
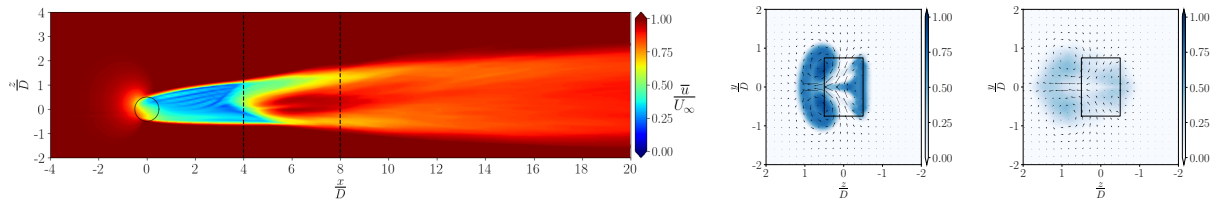


Figure 3.6: Contribution of the normal (green) and tangential (yellow) forces to the lateral force coefficient C_z

Wakes

In the figures (3.7, 3.8, 3.9, 3.10, 3.11) depicted below, five different pitch configurations are plotted. Subfigures on the left present the streamwise time-averaged velocity $\bar{u}$, normalized with the free stream velocity U_∞ on a horizontal mid-span plane. For each ϕ setup, the time-averaged normalized velocity deficits $1 - \frac{\bar{u}}{U_\infty}$ are shown on cross-stream sections respectively located 4 and 8 diameters behind the VAWT center. The velocity fields are averaged over the last $\hat{t} = 12.5$ dimensionless time of the simulations.

Figure 3.7: Blade pitch angle $\phi = -5^\circ$ Figure 3.8: Blade pitch angle $\phi = -2^\circ$ Figure 3.9: Blade pitch angle $\phi = 0^\circ$ Figure 3.10: Blade pitch angle $\phi = 2^\circ$ Figure 3.11: Blade pitch angle $\phi = 5^\circ$

Varying the blade pitch angle ϕ have a strong influence on the wake behavior. While P0 redirects moderately the wake, slightly inward pitch angles seem to have a stronger deflection ability. Looking at the mid-span planes, P5 and P2 have both an impressively deflected wake. The P5 setting shows a stronger influence over the near wake i.e. 0 to about 6 diameters past the wind turbine whereas the deviation is more progressive for P2.

As the blade pitch angle increases, the number of stripes inside the near wake, already present in the P-2 and P0 configurations, increases. P5 presents the most stripes, however, the general behavior of the wake is still coherent.

Figures (3.7, 3.8) do not present the outward pitch angle configurations as an effective way the deflect the wake. The forces produced are such that the resultant velocity field makes the wake collapse on itself. The wake mainly stays aligned with the wind turbine and presents modest vertical velocity deficit rejection.

In every configuration, the vorticity generated at the cylinder is mostly concentrated in 4 counter-rotating vortex tubes located at the cylinder's "corners". In the P-5 and P-2 configurations, the vorticity field is such that the wake is deflected mostly upward and downward. P5 and P2, as illustrated in figure (3.12), produce vorticity of opposite sign with a much more concentrated distribution in the case of P5. Those configurations produce a velocity field that deflects the wake sideways. The figure (3.12) presents the dimensionless averaged velocity deficit and vorticity fields 4 diameters downstream of the turbine for the P2 and P5 cases.

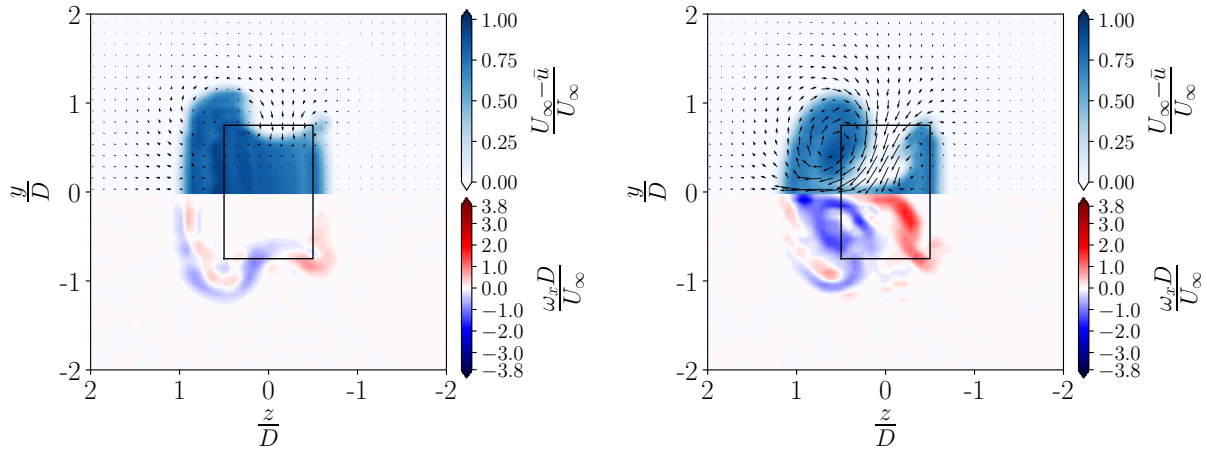


Figure 3.12: Averaged velocity deficit $\frac{U_\infty - \bar{u}}{U_\infty}$ and vorticity $\frac{\omega_x D}{U_\infty}$ fields 4 diameters behind the VAWT center : P2 (left), P5 (right)

Wake center tracking

In order to evaluate properly the effect of blade pitch angle ϕ over the wake deflection capacity of the turbine, a wake center can be tracked starting from the wake formation at the rotor to the downstream domain boundary. The choice is made to follow a method based of the "center of mass" of the velocity deficit [15]. With the VAWT positioned at the center of the domain and symmetric boundary conditions applied, the wake deflection is mainly lateral i.e., along the z -axis. The wake center transverse coordinate is given by the following equation where $\Delta\bar{u}(x, y, z) = U_\infty - \bar{u}(x, y, z)$.

$$z_c = \frac{\int \int z \Delta\bar{u}(x, y, z) dz dy}{\int \int \Delta\bar{u}(x, y, z) dz dy} \quad (3.3.3)$$

The wake centers are computed with the velocity field averaged over the last $\hat{t} = 12.5$ dimensionless time of the simulation in order to study a well-developed wake. The integrals are made over cross-stream sections of the domain located behind the wind turbine.

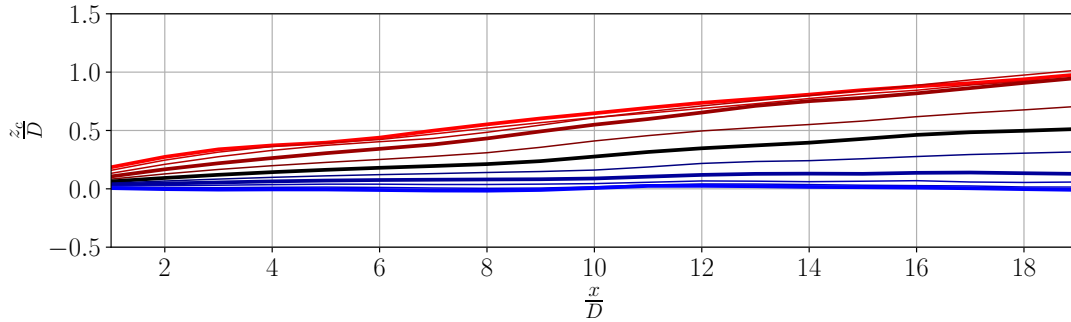


Figure 3.13: Wake center transverse coordinate z_c with respect to the streamwise distance behind the VAWT center for different blade pitch angle settings for P-5 (bluest) to P5 (reddest).

Figure (3.13) presents the evolution of the wake center transverse coordinate with respect to the streamwise distance downstream of the turbine. All pitch angle setups in the range $[-5^\circ; 5^\circ]$ are represented, with the curves corresponding to the velocity fields shown above depicted in bold.

Each curve exhibits a remarkable linear behavior and should eventually reach an asymptotic value in the far wake (which is not simulated in this work).

As expected, in the first few diameters, the P5 setup is the most deflective one. P2 exhibits a wake center deflection not as strong as P5 in the near wake. However, the two curves tend to a nearly similar value in the far wake. Past a 2° blade pitch angle, every configuration seem to tend to a common value of deflection.

It is noticeable that outward pitch settings makes the wake center stay aligned with the VAWT. P-2 imprints a small deviation while P-5 does not seem to deflect the wake at all.

Power

Finally, in order to deflect the wake while maintaining a consistent power coefficient, the previously found lateral force coefficients and wake center deflections need to be weighted with the corresponding power coefficient gathered in the table (3.4). The power coefficient is computed using the mechanical power output of the VAWT P_{mec} made dimensionless according to the relation (3.3.4).

$$C_P = \frac{P_{mec}}{\frac{1}{2}\rho U_\infty^3 H D} \quad (3.3.4)$$

ϕ	P-5	P-4	P-3	P-2	P-1	P0	P1	P2	P3	P4	P5
C_P	0.352	0.368	0.381	0.389	0.394	0.3943	0.391	0.382	0.363	0.332	0.281

Table 3.4: Power coefficients for each pitch configuration

First, we observe that power losses for outward configurations are significantly less pronounced at high blade pitch settings compared to inward settings, as previously noticeable in figure (3.2b). This difference is attributed to reduced blade exposure to stall during rotation and the second positive bump in tangential force in the downstream part of the rotor, as depicted in figure (3.5c). However, outward blade pitch settings do not produce sufficient lateral force to be relevant for the rest of this thesis.

Although P5 exhibits the highest lateral force generation, the power output decreases by 28.7% compared to the P0 configuration. In the other hand, P2 exhibits a strong deviation, see figure (3.13) while keeping a consistent C_P . With respect to P0, P2 suffers from a minor power loss of 3.1%. Pitching the blade more than 2° leads to higher power losses without increasing much the deviation. While a 1° pitch generates more power, it is noticeably not as effective as a 2° pitch in deflecting the wake.

3.4 Effect of the velocity profile

A uniform inflow velocity profile does not represent accurately the wind conditions observable in reality. In order to get closer to physical results, the presence of the ground as well as a boundary layer shaped velocity profile is to be taken into account. This section shows the influence of the velocity profile over the turbine's power production capacity for several inward pitch angle settings.

3.4.1 Methodology

Turbine's configurations

The turbine studied in this section is the same as the one used previously. According to the previous section, an inward fixed blade pitch angle deflects noticeably the wake. Focus will thus be put on 3 inward configurations: P0, P2 and P4.

The turbine is firstly simulated using fixed tip speed ratios to given values around the respective optimal values gathered in table (3.2). Secondly and for the rest of the study, the controller is activated and calibrated with the same data as the previous section. The effect of the ground as well as the velocity profile is then assessed.

Numerical setup

The studied domain is the same as that used in the previous section, with identical dimensions, resolution and boundary conditions. The wind turbine is placed 4 diameters downstream of the inflow and centered with respect to the transverse direction. To observe the effect of an impermeable lower boundary, the VAWT has a ground clearance, i.e., the distance between the ground and the lower part of the cylinder, of 21 meters. It should be noted that a wall model was not used in these simulations.

Two different inflows are considered. First, a uniform inflow with $U_\infty = 11$ m/s. Second, a logarithmic velocity profile, where the velocity field reaches 11 m/s at the height corresponding to the middle of the blade span. The uniform and logarithmic profiles are depicted on figure (3.14) with a representative turbine position.

For both inflow conditions, a time step of $\Delta t = 0.05$ s is used. The CFL number tends to be higher with the logarithmic profile. However, the previously taken safety margin is sufficient to avoid numerical instabilities. Finally, all simulations are performed over a dimensionless time $\hat{t} = \frac{tU_\infty}{D} = 100$. The flow and turbines quantities are studied and averaged during the last 12.5 dimensionless time.

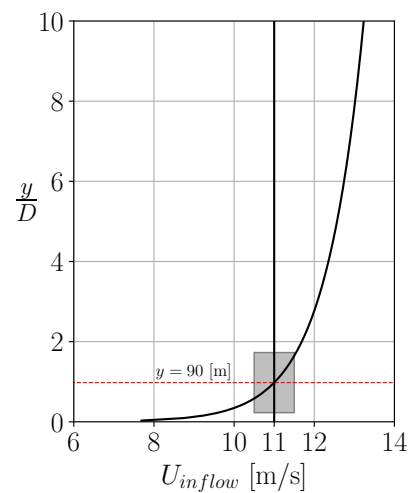


Figure 3.14: Inflow velocity profiles

3.4.2 Diagnostics and performances

Loads and Power

The power output can be compared between the uniform and logarithmic inflow cases. The velocity used for the adimensionalization of the power is the velocity at the mid-plane for the turbine, $U_\infty = 11$ m/s. The latter is the same for both cases. Figure (3.15) shows the evolution of the power coefficient for the 3 blades pitch angle settings considered under fixed tip speed ratios. The same U_∞ is used for the tip speed ratios.

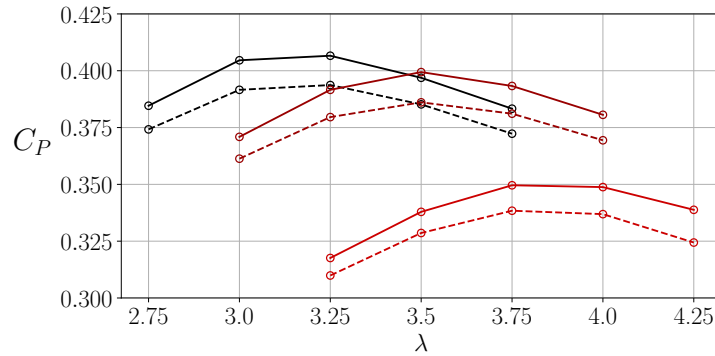


Figure 3.15: Power curves comparison, uniform inflow (solid), logarithmic inflow (dashed). Comparisons made for 3 inward pitch settings from black to red : 0° , 2° , 4°

From the figure above, it is evident that the velocity profile significantly impacts the mechanical power output of the rotor. The power produced by the VAWT in a uniform flow is consistently higher than in a logarithmic-shaped flow. Additionally, compared to the case studied in the previous section, the presence of the ground slightly increases the power coefficient.

While introducing the controller for the rotational speed, it was observed that the presence of the impermeable lower boundary in the domain does not significantly shift the λ of the turbine's optimal operating point under uniform inflow. The controller was not calibrated using logarithmic inflow data. However, since the maximum values observed in the logarithmic inflow case occur at approximately the same λ_{opt} as in the uniform inflow case, the controller performs effectively with logarithmic inflow as well.

With a uniform velocity inflow, the local tip speed ratio at a given height of the turbine remains relatively constant compared to the logarithmic inflow case. In the latter, the lower part of the VAWT experiences a higher tip speed ratio λ , while the upper part experiences a lower λ . Due to the high tip speed ratio in the lower part of the rotor, the angles of attack experienced by the blades do not vary as much as in the uniform inflow case. Consequently, the stall phenomenon observed in the previous section is less pronounced. However, since the angle of attack is slightly reduced (see figure (3.17)), only a small region of the airfoil polar is swept, leading to a decrease in the force produced. Combining these two observations, it is found that the contribution of the lower part to the power output is decreased for a logarithmic-shaped inflow.

Conversely, in the upper part, the angles of attack experience a wider range of values along a rotation, making the upstream part of this region more susceptible to stall. On the other hand, the downstream part experiences higher angles of attack with a logarithmic velocity profile than with a uniform one (see figure 3.17). Taking these two phenomena into account, the contribution of the upper part to power production is increased in the logarithmic case.

The contributions of the lower and upper parts of the turbine to the optimal power coefficient are presented in figure (3.16) for P0, P2, and P4 configurations. Overall, the VAWT experiences an average loss of 3% in a logarithmic flow compared to a uniform flow. It should be noted that the proximity to an impermeable boundary slightly shifts the power distribution from the upper part to the lower part of the rotor.

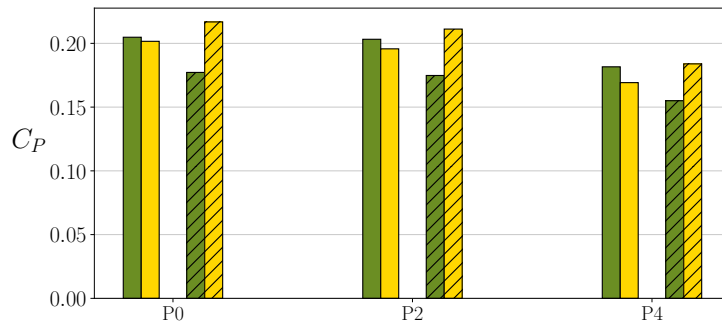


Figure 3.16: Power coefficient distribution between lower (green) and upper (yellow) part of the rotor. Hatched bars correspond to the logarithmic inflow case.

Focusing on the loads over the cylinder, the velocity profile seen by the turbine affects the load distribution from the bottom to the top of the rotor. The group of figures (3.17) show the time-averaged angles of attack, the normal forces and tangential forces at different heights y'^1 for each inflow and blade pitch angle considered.

Only small differences can be observed between the uniform and logarithmic inflow cases. It must be noticed that in the case of a logarithmic inflow, the angles of attack behaves in opposite manner from the lower part of the turbine to the upper one while in the uniform inflow case, α remains approximately similar.

As explained above, the stall of the cylinder will be pronounced in the upper part of the rotor. The higher absolute values of the angle of attack experienced in the downstream part, i.e., $\theta \in [180^\circ; 360^\circ]$, generate an increased tangential force, thereby enhancing the power. The inverse observations are also observable in the lower part of the turbine due to lower incidence. To address the flow velocity distribution and reduce induced losses, introducing a geometric twist angle along each blade could be an effective strategy to compensate for variations in the angle of attack.

¹ $y' \in [0, H]$ where $y' = 0$ and $y' = H$ are respectively the bottom and top of the rotor

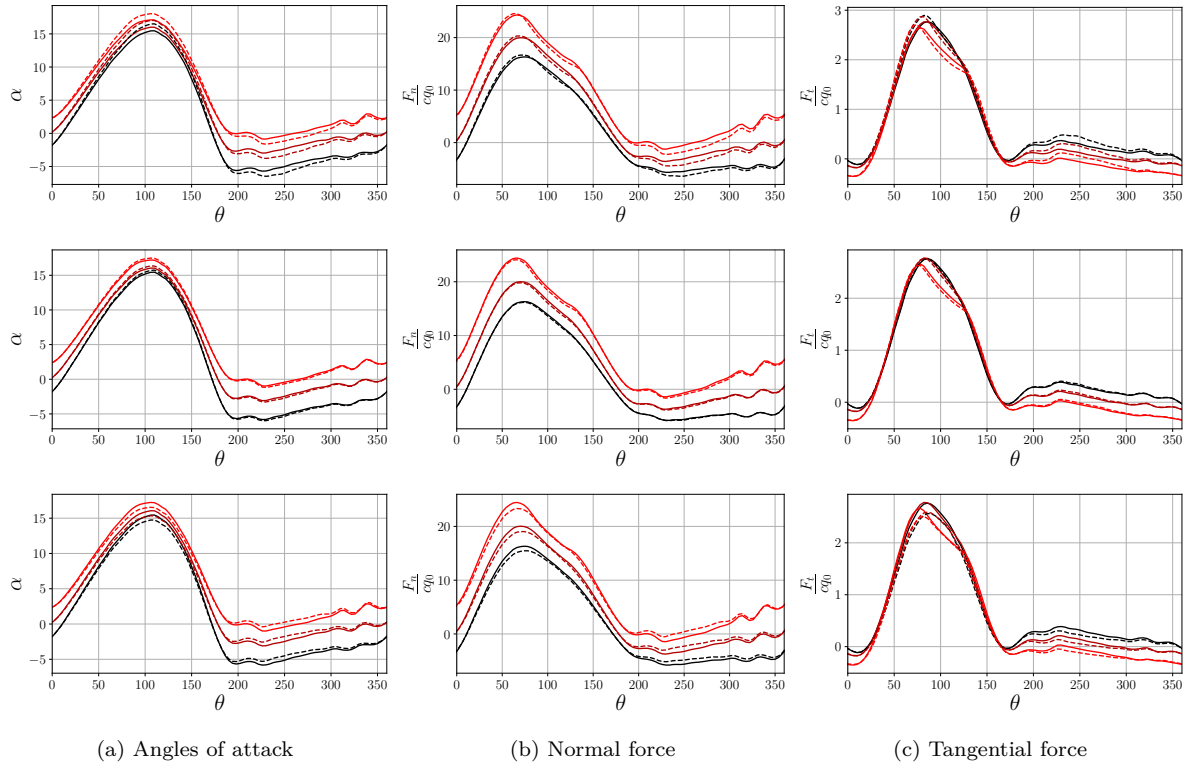


Figure 3.17: Time-averaged AoA's, normal and tangential forces at different levels of the turbine from top to bottom : $\frac{y'}{H} = \frac{3}{4}, \frac{1}{2}, \frac{1}{4}$ and for $\phi = 0^\circ$ (black), 2° (dark red), 4° (red). Solid and dashed line correspond to uniform and logarithmic inflow respectively

By computing the total lateral force created by the cylinder, it can be seen that the latter is slightly affected by the velocity profile. The lateral force coefficients are depicted on figure (3.18) with respect to the blade pitch angle. From this figure, it can be noticed that a VAWT working in a logarithmic-shaped wind experiences a 2% to 3% decrease in lateral force generation.

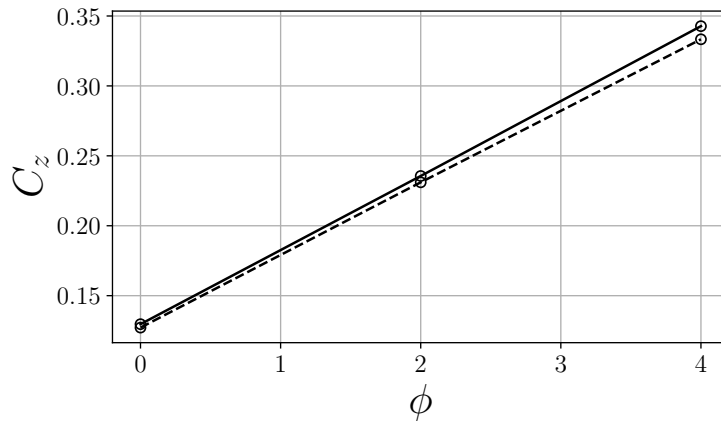


Figure 3.18: Lateral force coefficient with respect to the blade pitch angle for uniform (solid), logarithmic (dashed) inflow cases

3.5 Conclusion

This chapter provides an insight over the behavior of a single vertical axis wind turbine within uniform and logarithmic-shaped flow. Based on the results of the simulations discussed above, several conclusions can be drawn.

It has been shown that introducing a fixed blade pitch angle on the blade modify considerably the loads distribution over the actuator cylinder. The overall lateral force produced by the turbine scales remarkably linearly with the blade pitch angle introduced. On the other hand, the introduction of a pitch angle degrades noticeably the mechanical power output of the rotor for high blade pitch setting. A trade-off between lateral force production and power output must be found.

Focusing on the overall shape of the velocity deficit, the introduction of a pitch angle encourages the formation/intensity of 2 contra-rotating vortices located around $\theta = 0$. Pitching the blades either outward or inward create vortices of opposite signs that deflects the wake sideways. Inward pitch moves the wake center away from the VAWT imprint while an outward pitch makes it stay approximately aligned with the rotor. It has been observed that a pitch of 2° inward provides a great wake center deflection while keeping a substantial amount of mechanical power produced.

Finally, the turbine has been studied in more realistic inflow conditions. Due to the velocity profile, lower and upper parts of the rotor do not behave in the same manner and losses appear either from stall or to low angles of attack. The turbine then suffers from a light drop in power and lateral force generation capacity.

Chapter 4

Double rotor wake dynamics

4.1 Introduction

When working in a wind farm, the wake effects from an upstream wind turbine can be problematic to a downstream rotor. The wakes generated by upstream turbines can substantially diminish the power output of downstream turbines and increase the fluctuating forces on their blades, resulting in accelerated fatigue and a shortened lifespan. To prevent this reduction in lifespan and maintain significant power output from a system of rotors, it is crucial to investigate wake control strategies and quantify the impact of turbine spacing and blade pitch angle on performance.

This brief chapter aims to evaluate the effects of spacing between two VAWTs positioned in tandem, while also considering a blade pitch configuration to deflect the wake. This approach follows the strategy demonstrated in [32] and [26] for horizontal axis wind turbines, where a fixed yaw angle was used to control wake trajectory, thereby enhancing power production by reducing wake interaction between upstream and downstream turbines.

4.2 Methodology

4.2.1 Wind turbines

The model of wind turbine used in this chapter is the same as in the previous chapter i.e., an actuator cylinder composed of 24 rings in the spanwise direction each one counting 90 azimuthal points evenly distributed. The dimensions of the VAWT are listed in the table (3.1).

The first rotor is located 4 diameters downstream of the inflow and is centered along the vertical and transverse directions. Turbines are positioned exactly one behind the other, and four inter-distances, denoted as x_{sep} , are examined: 4, 6, 8, and 10 diameters. For each distance setup, 6 blade pitch angles are investigated: 0° , 1° , 2° , 3° , 4° and 5° . The pitch convention used is the same as for the previous chapter. The blade pitch setting is identical for both VAWTs and is fixed throughout the simulation. The controller is used and is calibrated with the same $(\lambda_{opt} - C_{P,max})$ couples as in the previous chapter.

4.2.2 Numerical setup

The rotors are placed in a parallelepiped domain of dimensions $[34D \times 10D \times 10D]$ in streamwise, vertical and transverse directions respectively. The boundary conditions are identical to the previous set of simulations. Uniform inflow of 11 m/s and an outflow condition are applied streamwise while slip conditions are applied over the bottom and top boundaries. Periodic conditions are imposed on both lateral sides.

The domain is meshed uniformly using 16 points per diameters. The resulting spatial increment is thus $\Delta x = 5.75$ m. A maximal time step of $\Delta t = 0.05$ s is used to avoid computational instabilities.

Simulations are performed over $\hat{t} = 200$ dimensionless time in order to let the wakes develop which correspond to 33440 iterations for the chosen time step. The flow and turbines quantities are studied and averaged during the last 50 dimensionless time.

4.3 Effect of the turbine inter-distance

In the following section, the lateral force of the downstream turbine is evaluated and power coefficients are computed for both turbines in every inter-distance and blade pitch angle setting.

4.3.1 Lateral force

Figure (4.1) shows the lateral force coefficients C_z of the downstream turbine for various turbine inter-distances x_{sep} and blade pitch angle configurations. The C_z of the first VAWT is not plotted, as its values exhibit minimal variation with changes in turbine spacing. However, the coefficients for both VAWTs are presented in table (B.1) and compared with those from a single turbine case with the same pitch.

C_z is highly dependent on both parameters, with the lowest coefficients occurring at small x_{sep} and low blade pitch angles. For these low values of x_{sep} and ϕ , the downstream VAWT stands within the wake of the upstream rotor, leading to reduced velocity and decreased generation of lateral forces.

By increasing the spacing x_{sep} and the pitch angle ϕ , the second VAWT exhibits a higher C_z due to its reduced interaction with the upstream VAWT's wake, which is deflected away as a result of the increased pitch setting. In the optimal scenario, 10 diameters spacing and a 5° pitch, the C_z coefficient of the downstream rotor reaches approximately half of the value attained in the single VAWT case.

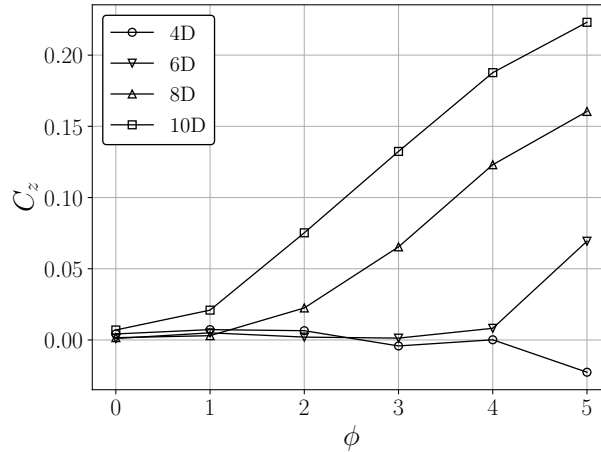


Figure 4.1: Time-averaged lateral force coefficient of the downstream rotor for several turbine inter-distances x_{sep} : 4D, 6D, 8D, 10D

4.3.2 Power

Figure (4.2) presents the power coefficients of the downstream turbine versus its blade pitch setting for the 4 turbine inter-distances introduced earlier. The first VAWT performances are not plotted as their values do not exhibit large variations with the turbine inter-distance. The power coefficients of both VAWTs are gathered in table (B.2).

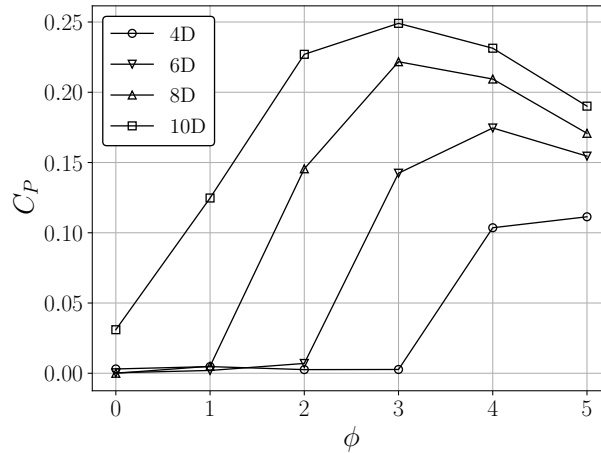


Figure 4.2: Time-averaged power coefficient of the downstream rotor versus the blade pitch setting ϕ for several turbine inter-distances x_{sep} : 4D, 6D, 8D, 10D

The power output of the downstream turbine is significantly influenced by the wake generated by the upstream turbine, particularly at reduced inter-turbine distances and low inward blade pitch angles. We can observe that the power coefficient do not completely vanish for short x_{sep} . The wake deflection caused by the highly pitched blades allows the downstream VAWT to maintain some power production. thereby preventing a total drop in the power coefficient even at small inter-turbine distances.

However, the maximum power coefficient achievable by a turbine decreases with the blade pitch angle. This maximum value acts as an upper bound to which C_P tends for high

values of x_{sep} . It becomes then convenient to evaluate the overall power production of both VAWTs. Figure (4.3) presents the total dimensionless power output, along with the individual contributions from each VAWT. In each blade pitch configuration, the total C_P for each x_{sep} is shown from right to left, representing inter-distances from 4D to 10D. Within each bar, the contribution from the upstream VAWT is displayed in green, while the contribution from the downstream VAWT is shown in yellow.

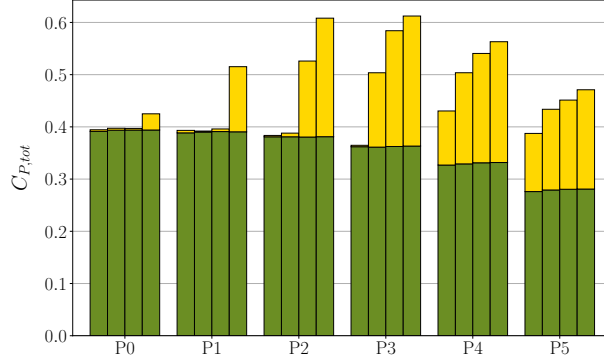


Figure 4.3: Total power coefficient and contribution from each VAWT

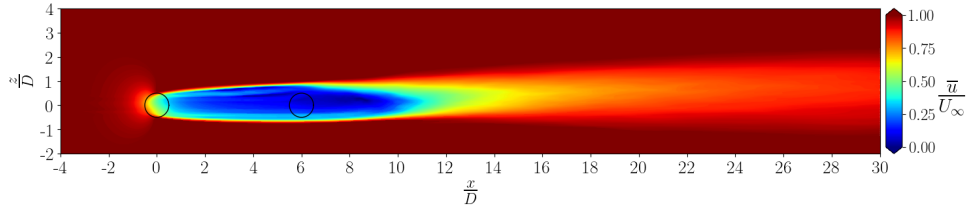
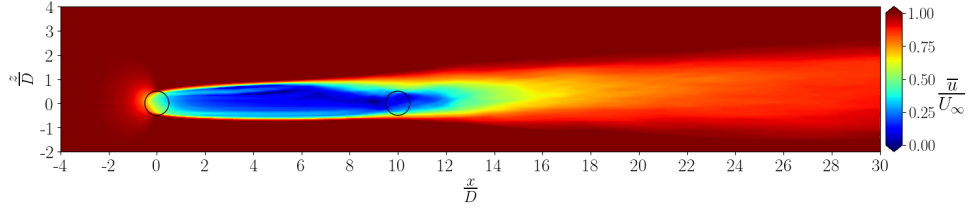
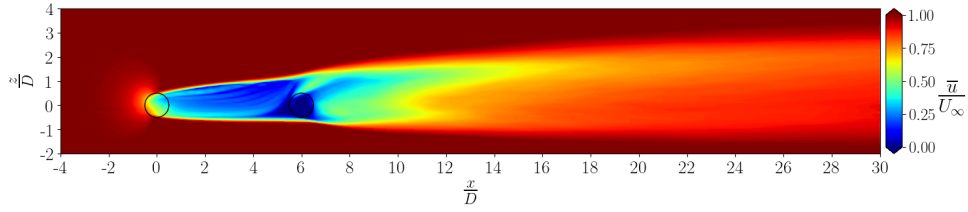
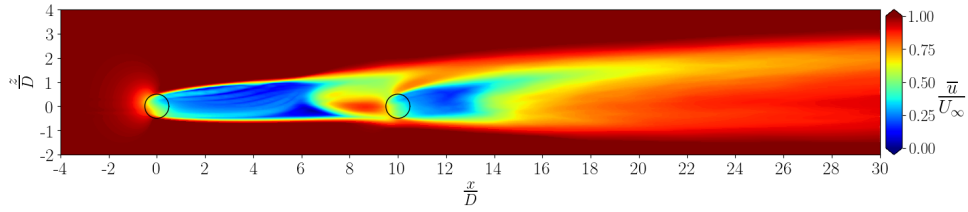
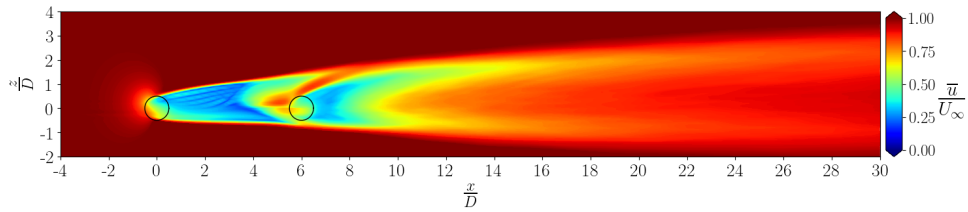
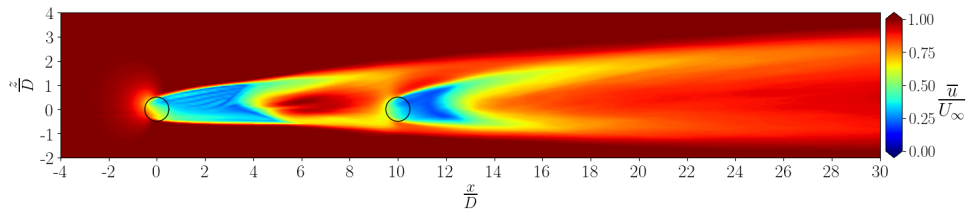
In the P0 configuration, increasing the spacing between turbines does not significantly affect the power production of the downstream wind turbine. In fact, all other configurations either match or exceed the performance of the P0 configuration. Introducing an inward blade pitch angle tends to enhance the overall power output of both turbines. Specifically, the deflection of the wake from the first turbine allows the downstream turbine to generate a considerable amount of power.

Increasing the separation distance x_{sep} enables the second vertical axis wind turbine to access a higher velocity field, thereby increasing its power output. However, the power gain per increment in x_{sep} decreases rapidly as x_{sep} becomes larger, especially for high values of ϕ . The maximum overall power output of 0.612 is achieved with $x_{sep} = 10D$ and a blade pitch angle $\phi = 3^\circ$.

4.3.3 Wakes

Hereunder are depicted the time-averaged normalized streamwise velocity fields $\frac{\bar{u}}{U_\infty}$ on a mid-span plane for inter-distances of 6 and 10 diameters and corresponding to $\phi = 0^\circ, 3^\circ, 5^\circ$.

The figures (4.7, 4.8, 4.9) show that on the mid-span plane, the streamwise velocity field appears to be higher in front of the downstream turbine than in the case of figures (4.4, 4.5, 4.6). This partly explains the values of power coefficients observed earlier. In addition to the small wake deflection, the values of C_P are also partly attributed to the uniform inflow condition. The latter results in lower turbulence intensity and consequently leads to poor wake recovery along the streamwise direction in the studied configurations.

Figure 4.4: $\frac{\bar{u}}{U_\infty}$ with $x_{sep} = 6D$ $\phi = 0^\circ$ Figure 4.5: $\frac{\bar{u}}{U_\infty}$ with $x_{sep} = 10D$ $\phi = 0^\circ$ Figure 4.6: $\frac{\bar{u}}{U_\infty}$ with $x_{sep} = 6D$ $\phi = 3^\circ$ Figure 4.7: $\frac{\bar{u}}{U_\infty}$ with $x_{sep} = 10D$ $\phi = 3^\circ$ Figure 4.8: $\frac{\bar{u}}{U_\infty}$ with $x_{sep} = 6D$ $\phi = 5^\circ$ Figure 4.9: $\frac{\bar{u}}{U_\infty}$ with $x_{sep} = 10D$ $\phi = 5^\circ$

4.4 Conclusion

Several conclusions can be drawn from the results regarding the effect of an upstream turbine on a downstream one:

The lateral force coefficient strongly depends on turbine spacing. At $x_{sep} = 4D$, the lateral force nearly vanishes for all blade pitch angles, while at $x_{sep} = 10D$, it reaches about half the value of a single VAWT case. Consequently, the downstream VAWT experiences significant lateral force reduction due to the upstream turbine's wake.

Redirecting the wake with a fixed blade pitch angle reduces the upstream VAWT's power coefficient but enhances that of the downstream VAWT, leading to an overall increase in power coefficient compared to a case without blade pitch. The maximum overall power coefficient is achieved when $x_{sep} = 10D$, as both power and lateral force coefficients of the second VAWT increase with spacing further increasing spacing would allow the second turbine to operate more like a single turbine, improving power production but decreasing power density. Thus, a 10-diameter spacing is maintained in the following chapter's wind farm VAWT layout.

Steep blade angles can decrease overall power output despite increasing downstream turbine performance. To maximize power generation in the VAWT tandem, it may be beneficial to set the downstream VAWT at a lower blade pitch angle than the upstream VAWT. This approach would allow the downstream turbine to benefit from the wake deflection of the upstream rotor while optimizing its own power generation.

It is important to note that these conclusions are based on uniform inflow simulations, where wake recovery is slower than in real conditions with turbulent mixing.

Chapter 5

Wind farm application

5.1 Introduction

This chapter presents an investigation of the use of vertical axis wind turbines with fixed blade pitch angles in a wind farm. From the previous chapters, an inward blade pitch setting has shown to be the most efficient one in term of lateral force introduction while keeping a substantial amount of power produced. This chapter aims at proving that atmospheric boundary layer control can be achieved by using the ability of a VAWT to generate lateral forces. In addition to deflecting the wake away from the downwind rotors, the turbines will be utilized in various configurations as vortex generators to create secondary flows, thereby re-energizing the flow within or behind the wind farm. The chapter focuses on the influence of fixed blade pitch angle setting as well as the rotation's directions on the overall wind farm power production.

5.2 Methodology

5.2.1 Wind turbines

Wind turbines are modelled using an actuator cylinder model and have the same parameters as in the previous chapters. Dimensions are given in table (3.1). In the case of a wind farm, Re_c is subject to impressive variations from a VAWT to another. On top of that, the ABL makes Re_c vary along the height of the turbine. The choice is made to use the same polar as in the previous chapters since the flow conditions are such that the $Re_c \approx 10^7$

As previously stated, a VAWT will adapt its rotational speed with respect to the incoming wind to reach its maximal power output. The controller is used and is calibrated with the same $(\lambda_{opt} - C_{P,max})$ couples as in the chapter 3 (see table (3.2)).

5.2.2 Numerical setup

Wind farm configurations are studied in a parallelepiped domain. Two types of wind farms are studied in this chapter. The first wind farm is infinitely wide and the second one is considered isolated. Studying a laterally infinite wind farm helps to approximate the flow behavior within a wind farm composed of many turbines. The isolated case provides

insight into the flow behavior at the edges of the wind farm. Two domain's transverse dimensions are then studied in this chapter. In the case of the infinitely wide farm, the transverse length is such that the distance between the side boundary and a side line of turbine is the half of the distance between 2 VAWTs lines. The transverse dimension for the case of an isolated wind farm is chosen to be twice the length used for the infinite farm. Periodic boundary conditions are applied to the lateral boundaries in both cases.

The streamwise and vertical dimensions are the same for both domains. The streamwise dimension is chosen in order to have a sufficient inter-distance between each row of VAWTs according to the previous chapter i.e., 10 turbine's diameters. The first row of turbine is spaced from the inflow by 6 diameters and 20 diameters separate the last row from the outflow. Finally, the height of the domain is chosen to be 8 diameters. The domain dimensions are thus $[5152 \times 736 \times 1472]$ and $[5152 \times 736 \times 2944]$ m. As a reminder the y-axis is aligned with the vertical direction.

In this chapter, the vertical axis wind turbines are placed in two different flows due to their inflow conditions:

1. A uniform inflow
2. An atmospheric boundary layer inflow

The uniform inflow case exhibits an inflow velocity on 11 m/s with slip conditions of lower and upper boundaries.

For the more complex case of an ABL, the inflow is generated using the procedure detailed in Chapter 2. At the bottom, wall effects are taken into account using a wall model and a wall roughness is applied to obtain an ABL profile of the freestream flow. The boundary layer used in this work is such that it reaches an average velocity of 11 m/s and a turbulence intensity of 6% at the height of the mid-span plane of the VAWTs. The ABL has been generated in a domain of size $32D \times 8D \times 16D$ with a resolution of 32 points per diameter up to an altitude of $2D$. The mesh is then vertically stretched up to $8D$ height. Hereunder is presented the time-averaged velocity profile of the resultant boundary layer used in this work.

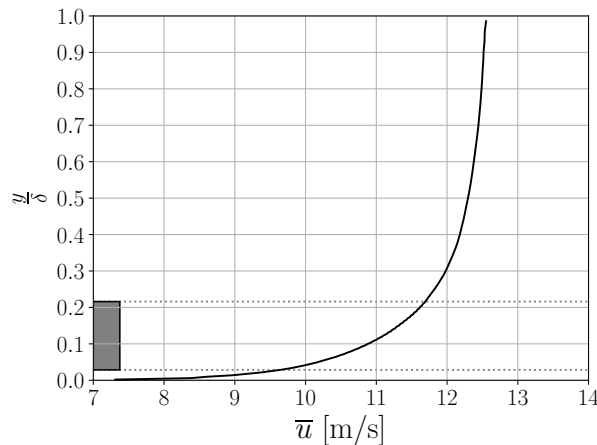


Figure 5.1: Time-averaged mean streamwise velocity profile

The ABL was initially generated only for the case of an infinitely wide wind farm. To avoid the considerable computational time required to obtain a sufficiently large ABL for the isolated cases, the same ABL has been assembled side by side to create a domain twice as wide.

Finally, a uniform spatial resolution in x , y and z of $\Delta x = 5.75$ m is used for the uniform flow simulations while stretching is applied on the y direction in the case of the ABL simulations. The time step used is chosen as $\Delta t = 0.05$ s for both inflow cases so that the maximum CFL number is sufficiently small to avoid instabilities.

5.3 Investigated configurations

In this chapter, several wind farm working scenarios are being studied. The position of the rotors with respect to each other is fixed and only the rotation's direction or the blade pitch angle are allowed to vary.

Two rotation configurations are investigated beside of a reference one. Those configurations are named "Mirror" and "Alternating". The configurations are detailed below. For each of those three configurations, 3 different blade pitch angle setups are considered. For each wind farm type, flow condition, and rotation setup described above, a 0° , 2° , or 4° inward pitch is applied to every rotor in the simulation. The pitch angle is the same for all rotors within the farm and remains fixed throughout the simulation.

5.3.1 Reference

In order to make a fair comparison of the gain/loss of various wind turbines configurations, the choice is made to take the case of 16 vertical axis wind turbines without blade pitch angle for a reference wind farm. Due to the dimensions of the domain as well as the periodic boundary conditions applied on the lateral boundaries, the farm represent either a section of an infinite 4 rows wind farm or an isolated 4 by 4 farm. The turbines are positioned 4 diameters apart in the transverse direction and spaced 10 diameters apart in the streamwise direction. Each turbine rotates counterclockwise when viewed from above. The wind farm is centered along the width of the domain and, as previously stated, the first row of VAWT is placed 552 m from the inflow i.e., 6 diameters. Every turbine has a ground clearance of 21 m i.e., the lowest part of the blades is 21 m high. The disposition of the rotor is presented on figures (5.2) and (5.3).

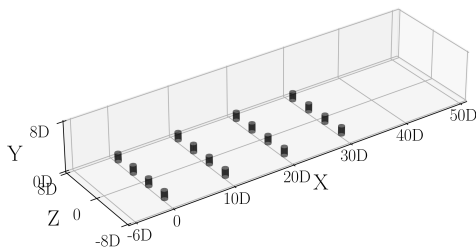


Figure 5.2: Infinite farm domain

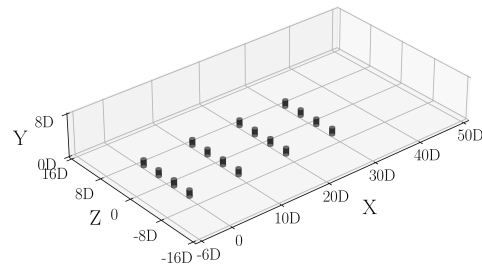


Figure 5.3: Isolated farm domain

5.3.2 Mirror and Alternating

In the mirror configuration, half of the previously introduced 16 VAWTs rotate clockwise while the other half rotate counterclockwise. This configuration aims to generate a large secondary flow structure above the VAWT, which pumps down the high-velocity flow higher in the boundary layer. The configuration is presented in figures (5.4a). By arranging the rotation in an alternating pattern within a row, the alternating configuration aims to develop smaller yet more numerous vortex structures above the farm. A representation of this configuration is shown on figure (5.4b).

Due to periodic boundary conditions, reversing the rotation direction in the infinite wind farm setup gives the same results, only, shifted in space. However, this is not the case with the isolated wind farm. Given the considerable computational time required for each simulation, the study focuses on the reference setup and the configurations presented hereunder with this specific rotation direction variant.

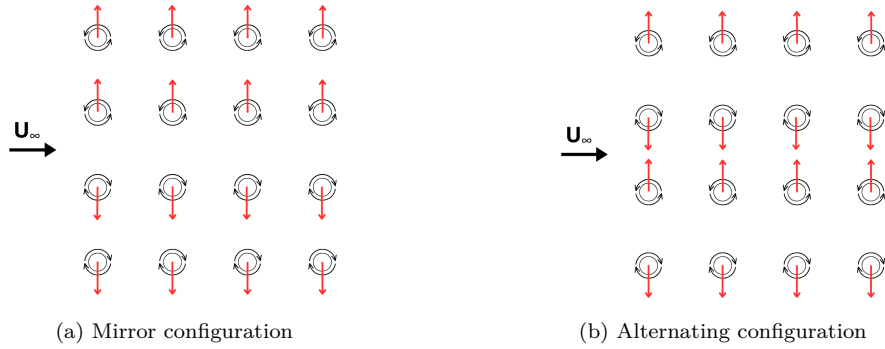


Figure 5.4: Both configurations represented with the corresponding expected direction of wake deflection

5.4 Uniform inflow

The wind farms are simulated during a dimensionless time $\hat{t} = 450$ with $U_\infty = 11$ m/s corresponding to approximately 8 flow-through. The flow and turbines quantities are studied and averaged during the last 300 dimensionless time units of the simulations.

The upper boundary is to be analyzed cautiously. Due to the imposition of a slip boundary conditions, the latter acts as an impermeable surface which is not physically correct. However, as shown in figures (5.11a) and (5.11b), the in-plane velocity fields are already nearly zero several diameters below this boundary.

5.4.1 Wakes

The figures (5.5, 5.6, 5.7) and (5.8, 5.9, 5.10) presented on the following pages show the time-averaged streamwise normalized velocity fields $\frac{\bar{u}}{U_\infty}$ on an horizontal plane intersecting the turbines at mid-span for the different cases.

It must be pointed out that in every configuration, the deflection of the wake is considerable for $\phi = 2^\circ$ or 4° . With a 0° blade pitch angle, the first row of rotors generates only a weak wake deflection. As the inflow is uniform, without turbulence, the wake recovery is slow. The second row is therefor strongly impacted by the first row wake. I thus experience a large power loss (see appendix C).

The flow demonstrates approximately similar behavior between the infinite and isolated cases. However, in the isolated case, both the mirror and alternating configurations exhibit slightly more dispersed wakes starting from the third row of turbines. Indeed, in the infinite farm scenario, the wake is constrained by the wake of neighboring turbines, causing a lateral blockage.

In the reference configuration, increasing the blade pitch angle inward for each VAWT generates a lateral current at the level of the farm. The lateral flow becomes more pronounced as the observer moves downstream as well as ϕ is increased. In the case of $\phi = 4^\circ$ the wake of the third row is sufficiently deflected sideways to interfere with a VAWT of the fourth row located in the adjacent line.

In the mirror and alternating configurations, the wakes are pushed into each other. The lateral flow observed in the reference configuration cancels out where two wakes meet or at the middle of two diverging one. This complex flow interaction combined with the presence of the ground acts as a "pump" that generates an either upward or downward vertical secondary flows.

Infinite wind farm : Time-averaged normalised velocity in horizontal plane at mid-span for each configuration

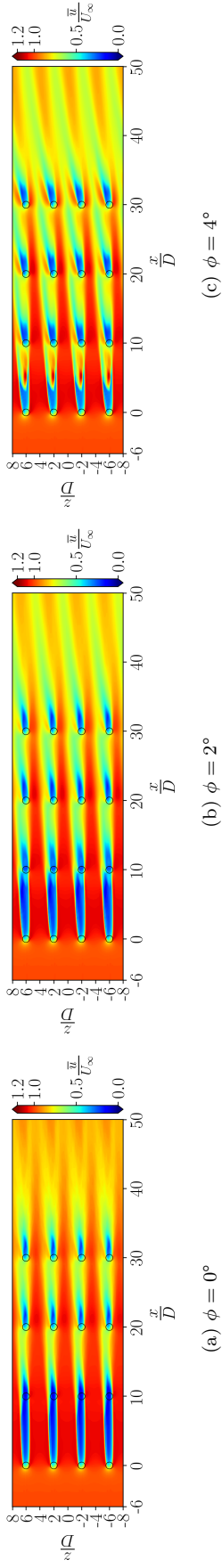


Figure 5.5: Reference configuration

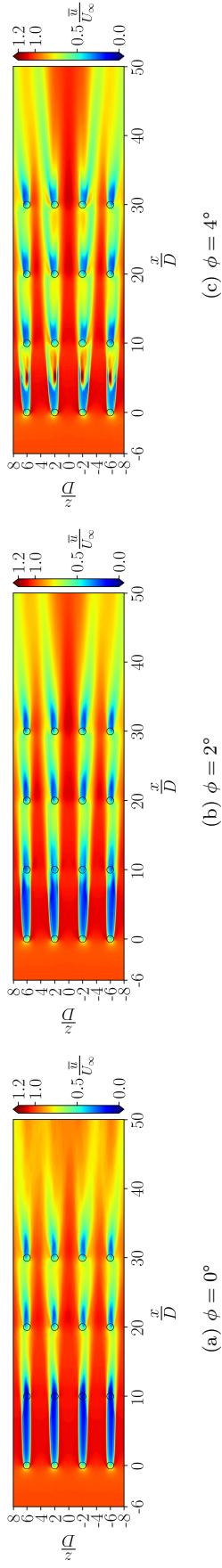


Figure 5.6: Mirror configurations

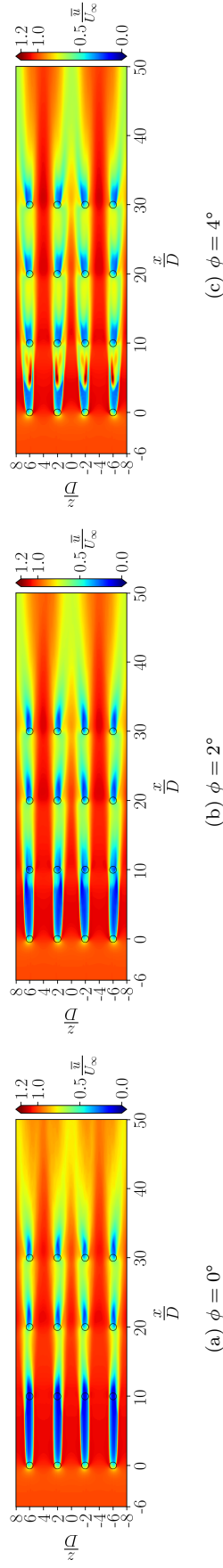


Figure 5.7: Alternating configurations

Isolated wind farm : Time-averaged normalised velocity in horizontal plane at mid-span for each configuration

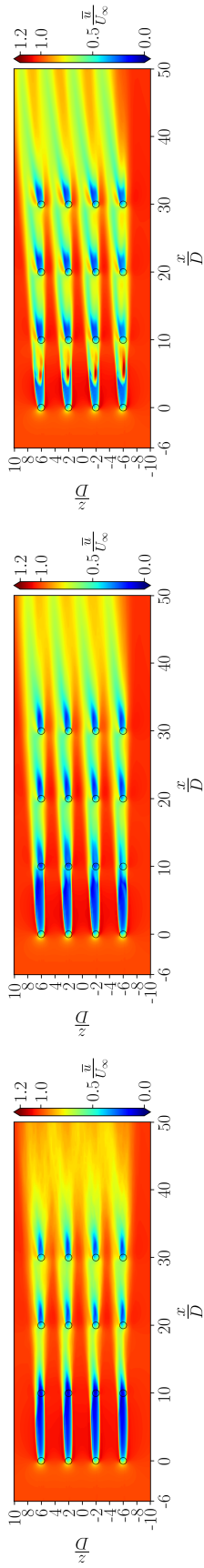
(c) $\phi = 4^\circ$ (b) $\phi = 2^\circ$

Figure 5.8: Reference configurations

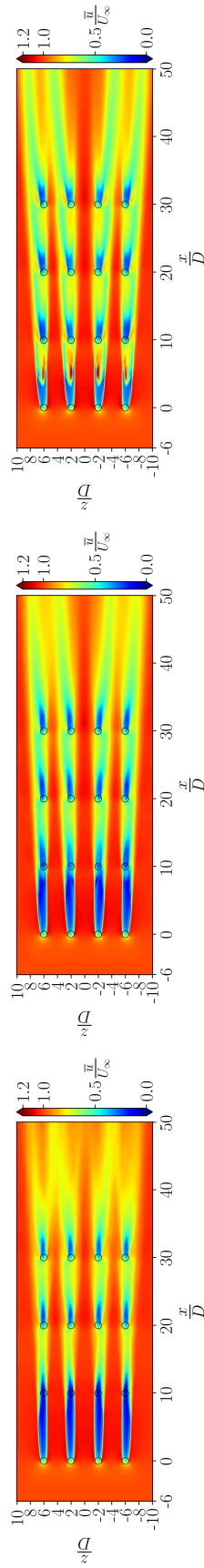
(c) $\phi = 4^\circ$ (b) $\phi = 2^\circ$

Figure 5.9: Mirror configurations

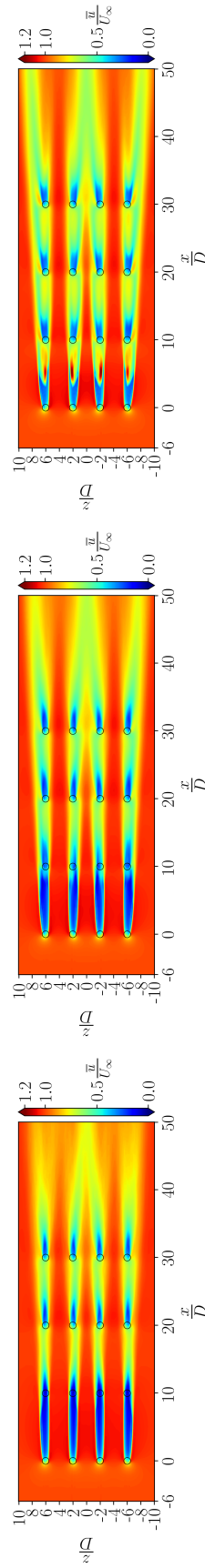
(c) $\phi = 4^\circ$ (b) $\phi = 2^\circ$

Figure 5.10: Alternating configurations

Focusing on cross-stream sections, the introduction of a blade pitch angle deflects markedly the wake, generating secondary cross-stream flows for every rotation configuration. In order to quantify the strength of the secondary flows the time-averaged in-plane velocity is measured.

$$\overline{V} = \sqrt{\overline{v}^2 + \overline{w}^2} \quad (5.4.1)$$

Figures (5.11a) and (5.11b) depict the streamwise velocity as well as the in-plane velocity for both infinite and isolated wind farms. Those slices correspond to P4 configurations on cross-stream sections at 5, 15 and 25 diameters downstream of the first row. The streamlines show the secondary flows in-plane directions. The choice was made to mask streamlines where the in-plane velocity is less than 1 percent of the free stream velocity U_∞ .

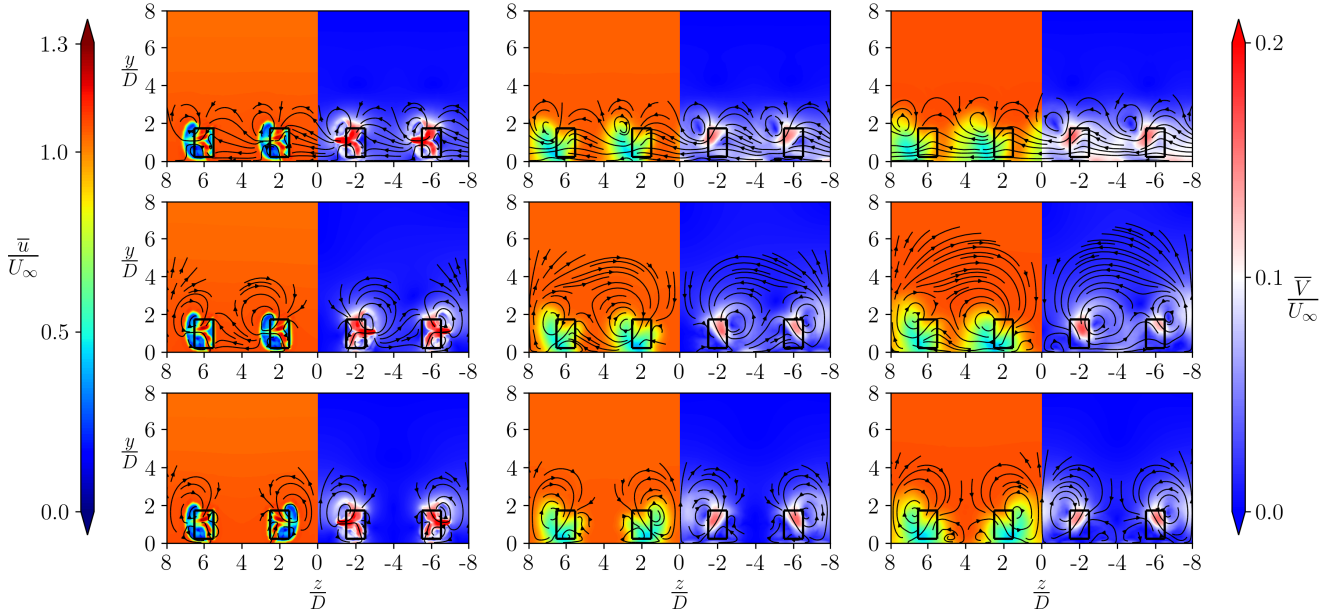
As previously observed, the reference configuration shows a strong lateral flow reaching, at the level of the VAWTs and at the end of the farm, 10% of the freestream velocity U_∞ in averaged. This lateral current does not appear in other rotation configurations. In the latter, an upward vertical flow is generated at the meeting point of two wakes, while a downward flow appears between two diverging wakes. In every case, the upward secondary flows appear stronger than the downward flows. We observe regions of high in-plane velocity aligned with lines of rotor that can reach up to 20% of the freestream velocity. These regions emerge from the P4 blade pitch configuration, which demonstrated earlier strong deflection capability.

It is worth noting that in the laterally infinite case, due to the infinite number of rotors in the farm, the induced vertical or lateral flows appear stronger than in the case of an isolated wind farm. Indeed, the high in-plane upward velocity regions observed at $\frac{z}{D} = \pm 8$ in the mirror and alternating infinite cases appear slightly reduced in the isolated case due to the absence of incoming wakes from the opposite direction. The velocity of the vertical current in the isolated case is nevertheless considerable, especially in the center of the alternating configured wind farm. The upward velocity regions present in the mirror and alternating cases are seen to reach up to 10% of the value of the freestream velocity.

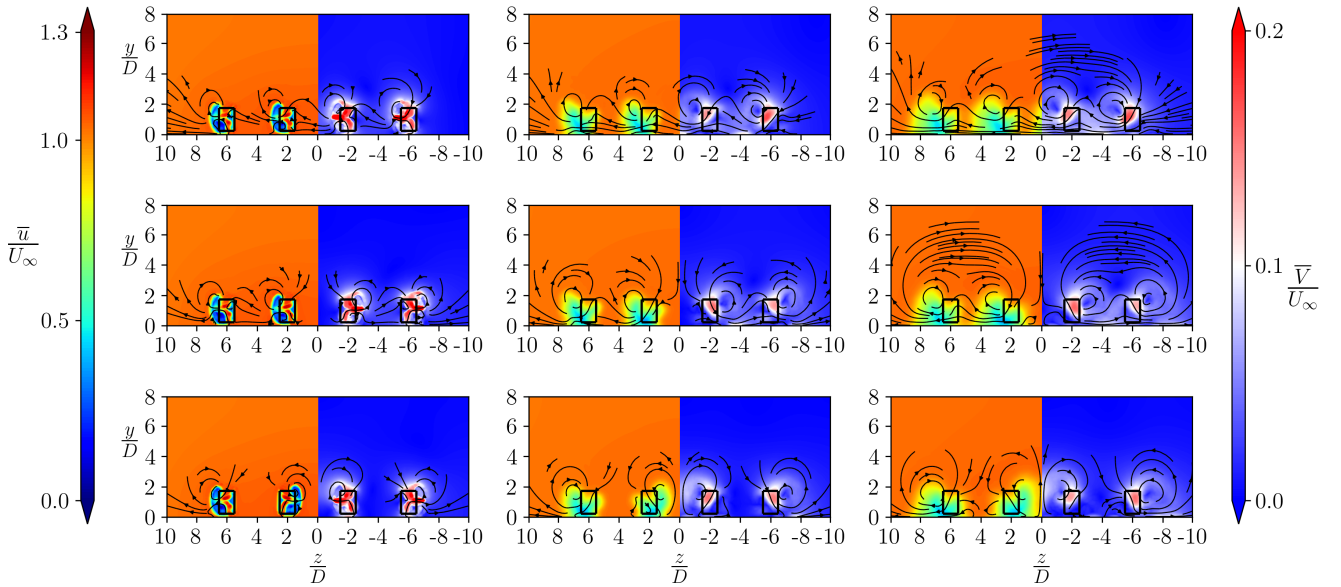
By analyzing the overall shape of the streamlines, it can be observed that the reference configuration generates vortex tubes near the top left corner of each VAWT line. In the isolated scenario, these vortex tubes exhibit less organized behavior and take more time to develop. Eventually, a global secondary flow emerges, introducing a lateral velocity higher up in the simulation domain. This flow moves in the opposite direction to the secondary flow generated at the level of the VAWTs.

In both the mirror and alternating configurations, VAWT lines appear to operate in pairs, generating two distinct vorticity fields. These vorticity fields are symmetric, and due to the rotational configuration, large pairs of contra-rotating vortex tubes are created. In the alternating configuration, these pairs consist of concentrated contra-rotating vortex tubes. Conversely, in the mirror configuration, they consist of larger groups of vortex tubes that still act in a contra-rotating manner above pairs of rotors rotating in the same direction. In both mirror and alternating setups, these regions increase in size as we move further into the wind farm, eventually stabilizing into consistent shapes. These configurations

thus enable higher interaction with the velocity field compared to the reference case. The difference between the infinite and isolated cases can be explained by the effect of the wind farm's edges. Indeed, since there are no wake side interactions at $\frac{z}{D} \pm 8$, the circular or lateral motions are not as constrained.



(a) Infinitely wide wind farm



(b) Isolated wind farm

Figure 5.11: Time-averaged streamwise (left) and in-plane (right) velocity fields in cross section planes at different locations : 5D (left), 15D (center) and 25D (right) downstream of the first row. Every P4 configurations are represented : reference (top) the mirror (middle) and alternating (bottom) cases

5.4.2 Power

Considering a 4 by 4 VAWTs section of the infinitely wide wind farm, the total power production of the installation can be assessed and compared hereunder with the isolated case. The total power production in MW of the infinite and isolated farms are respectively gathered below in tables (5.1) and (5.2). For each wind farm, the gain or loss are computed with respect to the P0 reference case of the corresponding wind farm.

	Reference	Mirror	Alternating
P0	39.1	37.7 (-3.4%)	36.0 (-7.8%)
P2	48.6 (+24.1%)	42.5 (+9.7%)	41.3 (+5.5%)
P4	47.1 (+22.1%)	40.9 (+4.4%)	39.3 (+1.7%)

Table 5.1: Infinite wind farm

	Reference	Mirror	Alternating
P0	36.2	35.8 (-1.0%)	35.3 (-2.26%)
P2	42.3 (+16.97%)	40.6 (+12.26%)	39.2 (+8.41%)
P4	41.1 (+13.74%)	39.6 (+9.58%)	37.7 (+4.36%)

Table 5.2: Isolated wind farm

The distribution of power within each wind farms is presented in figures (C.1a) and (C.1b) of the appendix (C).

Focusing on the impact of the rotation setup and the fixed blade pitch angle, the reference configuration generates more power compared to both the mirror and alternating configurations, given the same blade pitch angle setting. The mirror configurations present a slightly higher production than the alternating cases.

In the infinite wind farm, the reference P0 configuration shows a total power production of 39.07 MW with the power unevenly distributed among the turbines. Indeed, as well as for the mirror and alternating P0 cases, the wake of the first row presents poor recovery and deflection. This affects the second row of VAWTs, resulting in near-zero power production. In this case, the second row proves itself useless and only contribute to unnecessary expenses.

Then, increasing the blade pitch angle increases the total power production of every farm until reaching an optimal value corresponding to a $\phi \in]0^\circ; 4^\circ[$. Indeed, as the blade pitch is increased, the deflection of the wake produced by the first row increases as well. According to the figure (C.1a) and (C.1b) and visible on the midspan planes shown earlier, this deflection allows the second row, useless in a P0 scenario, to also produce a significant amount of power. However, in the P2 scenarios, the activation of the second row produces a longer wake that significantly reduces power output in the third and fourth rows in the mirror and alternating configurations.

The reference scenario sees the power output of its downstream rows enhanced as the blade pitch is further increased. The third and fourth rows of the reference configuration demonstrate their highest production levels with a blade pitch of 4° . This increase can be explained by the intensification of the secondary lateral flow observed earlier. Conversely, in mirror or alternating setups, this adjustment primarily reduces the power output of the first row, while the downstream rows maintain approximately the same power output.

Additionally, across all rows, and especially in the first row, a higher blade pitch angle decreases the power generation as it has been seen in previous chapters.

In the P2 infinitely wide wind farm in a reference configuration, the power increase reaches up to 24.1% compared to the corresponding P0 reference farm. This increase, along with the total amount of power generated, is greater in the infinite setup. This is attributed to the fact that the lateral secondary flow is slightly stronger in the infinite case than in the isolated one. Since the direction of the incoming wind does not affect vertical axis wind turbines, the velocity encountered by the downstream rows is slightly higher. Consequently, in this configuration, the second, third, and fourth rows produce moderately more power than they do in an isolated wind farm.

Globally, isolated wind farms exhibit lower power output compared to the infinite case. However, changing the rotation to a mirror or alternating configuration has a greater impact on power production gains in the isolated farm.

5.5 Atmospheric boundary layer

In the following section, the previously simulated wind farm stands within the atmospheric boundary layer presented earlier. The wind farm configurations are simulated during a dimensionless time $\hat{t}$ of 450 corresponding to approximately 8 flow-through at the height of the turbines. For every figure presented below, the resulting fields, flow and turbines quantities are averaged over the last 300 dimensionless time of the simulations.

5.5.1 Wakes

The figures (5.12, 5.13, 5.14) and (5.15, 5.16, 5.17) present the time-averaged streamwise normalized velocity $\frac{\bar{u}}{\bar{u}_\infty}$ on a horizontal plane intersecting the turbines at mid-span. Each blade pitch and rotation configuration are represented for infinitely wide and isolated wind farms.

It is worth noticing that in the regions $\frac{z}{D} \approx -8, -2, 8$ of the infinite wind farm inflow, the streamwise velocity fields on the mid-span plane appears either weaker or stronger. This behavior is inherently due to the atmospheric boundary layer's formation process. Some large turbulent structures become difficult to break down, particularly when the simulation domain is not sufficiently large. Those stronger or weaker spots have a small influence on the production of power of the nearby turbine. Due to the assembly process, these same structures can be found at $z \approx 0$ and 6 in the isolated cases.

It is important to note that the turbulent behavior of the ABL allows a faster momentum recovery within the wake [16] [17]. Compared with the uniform inflow case, the second row of turbine does not suffer as much from the first row's wake in the case of a zero blade pitch angle setting. It will be shown that this row actually produced a substantial amount of power even in a P0 setup (see appendix (C)).

Comparing the velocity fields in both infinite and isolated scenarios, we observe that the flow exhibits similar behavior overall. However, the isolated cases exhibit slightly less deflected wakes and weaker transverse velocity compared to the infinite scenario. In particular, in the P4 setups, the wake from the third row nearly avoids the fourth row in the infinite case, whereas it significantly impacts the fourth row in the isolated configuration.

Infinite wind farm : Time-averaged normalised velocity in horizontal plane at mid-span for each configuration

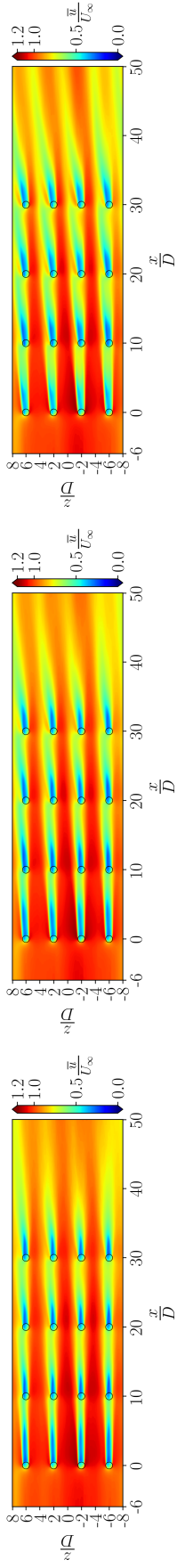
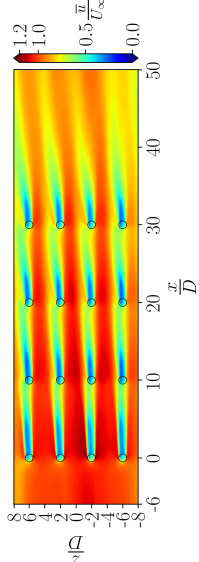
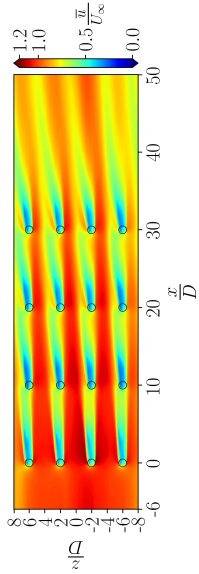
(a) $\phi = 0^\circ$ (b) $\phi = 2^\circ$ (c) $\phi = 4^\circ$

Figure 5.12: Reference configurations

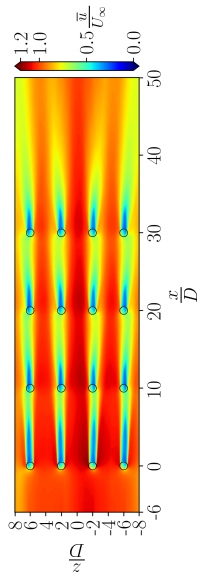
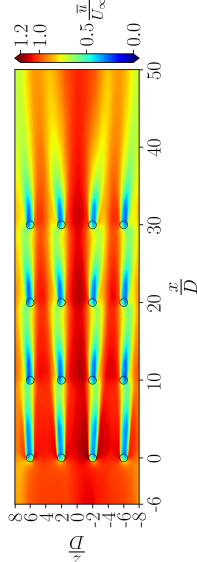
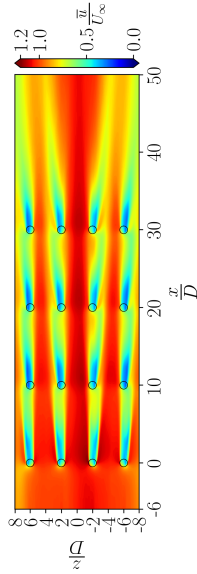
(a) $\phi = 0^\circ$ (b) $\phi = 2^\circ$ (c) $\phi = 4^\circ$

Figure 5.13: Mirror configurations

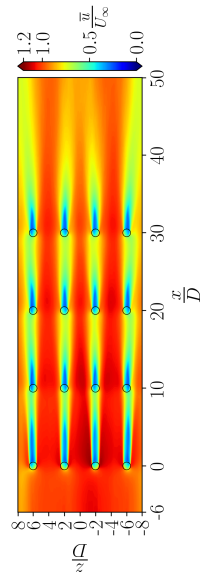
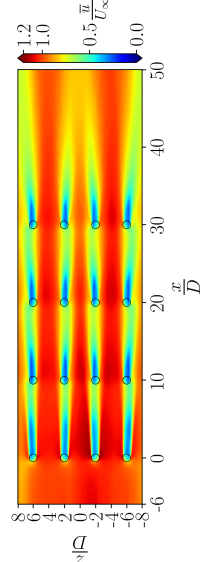
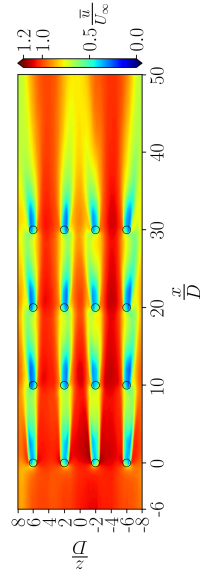
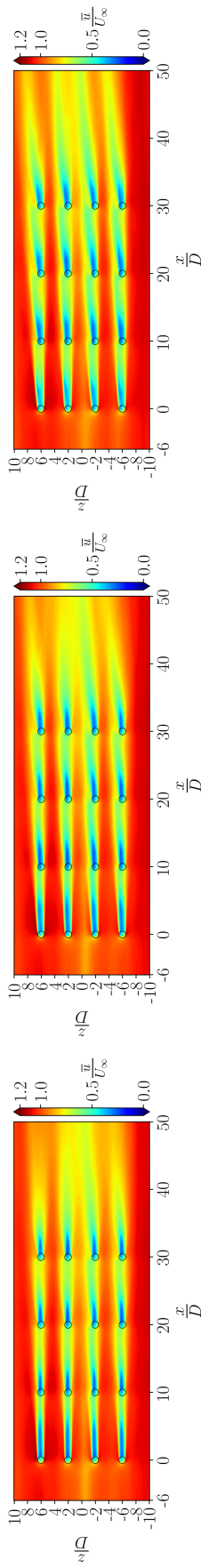
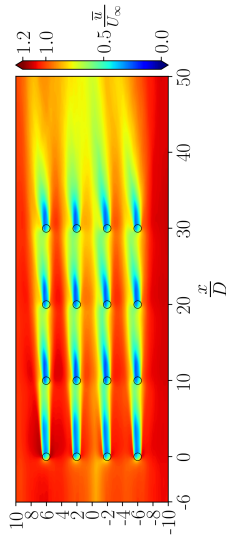
(a) $\phi = 0^\circ$ (b) $\phi = 2^\circ$ (c) $\phi = 4^\circ$

Figure 5.14: Alternating configurations

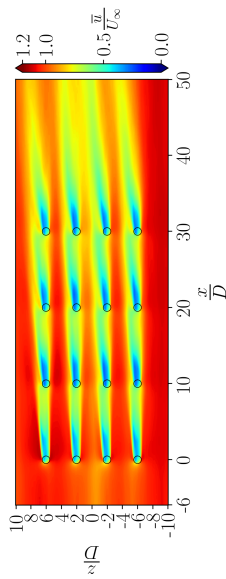
Isolated wind farm : Time-averaged normalised velocity in horizontal plane at mid-span for each configuration



(a) $\phi = 0^\circ$

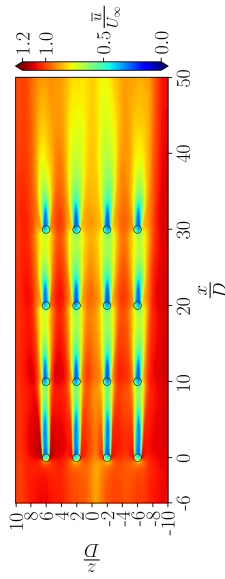


(b) $\phi = 2^\circ$

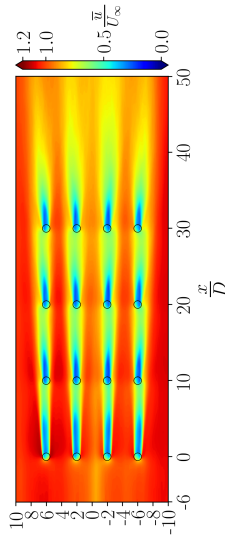


(c) $\phi = 4^\circ$

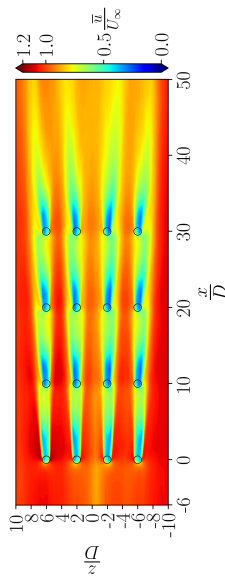
Figure 5.15: Reference configurations



(a) $\phi = 0^\circ$

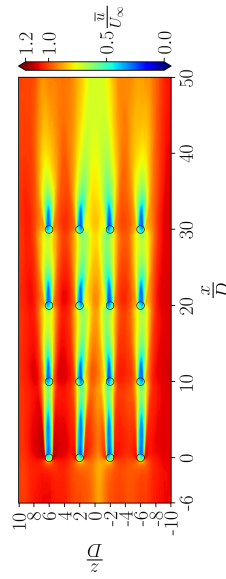


(b) $\phi = 2^\circ$

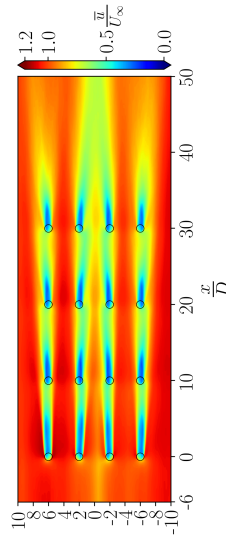


(c) $\phi = 4^\circ$

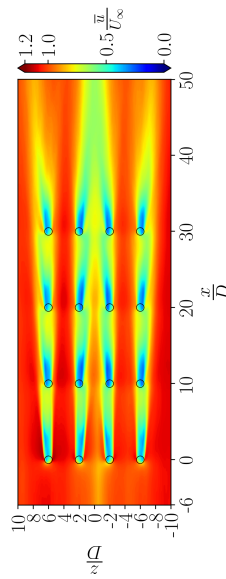
Figure 5.16: Mirror configurations



(a) $\phi = 0^\circ$



(b) $\phi = 2^\circ$



(c) $\phi = 4^\circ$

Figure 5.17: Alternating configurations

The figure (5.18a) gathers the time averaged normalized streamwise and in-plane velocity fields of each P4 configurations on cross-stream sections at $\frac{x}{D} = [5, 15, 25]$ i.e., between every row of turbines. Streamlines are displayed across the entire cross-sections, noting that the in-plane velocity at high altitudes remains negligible compared to the free stream velocity.

Looking at cross-stream sections of the flow, it must be noticed that the flows demonstrate approximately the same secondary flows structures as in the uniform inflow case. Due to the boundary layer shape of the velocity profile, a stronger shear appears above the wind farm and the mixing effect has a greater impact. These structures appear weaker and not as coherent than the ones observed in the previous section.

In the mirror and alternating farms, at the VAWTs height, the secondary flows adopt approximately the same behavior of pronounced upward and downward currents as in the uniform cases. However, these fluid motions are not as strong as in the uniform inflow scenarios. Regarding the cross-section 25 diameters behind the first row, the velocity deficit occupies slightly more of the VAWTs' imprints than under uniform inflow conditions. In other words, the wake deflection is not as marked and there is less fresh fluid with higher streamwise velocity reaching the next line of VAWTs. This will have for consequence to lower the power output of the last rows of turbines.

In the alternating case, the structures observed in the ABL inflow scenario do not reach the same altitude as their counterparts within a uniform inflow. At an altitude of about 3 diameters, they begin to collapse. These structures are thinner compared to those observed in the mirror or reference configurations, repeating alternately with a period of 4 diameters. This thinner profile makes them more exposed to the turbulent behavior of the atmospheric boundary layer.

Figure (5.18b) presents the same slices for an isolated wind farm. The fact that the wind farm layout is not infinitely wide anymore makes the flow structures observed in the previous configuration noticeably less coherent. In the mirror scenario, the large circular fluid motions observed earlier are no longer visible. Turbines appear to operate nearly independently of each other. In the reference case, a lateral secondary flow is noticeable but weaker than in the infinite farm. Finally, in the alternating configuration, the upward motion at the center of the farm seems to persist. This secondary flow is also associated with a downward velocity around $z = \pm 4D$.

In general, and as observed earlier in the uniform inflow scenario, the isolated wind farm does not exhibit the same flow patterns as an infinite farm. This discrepancy arises from the absence of turbines at the edges of the farm, which prevents the generation of strong circular fluid motions in these regions.

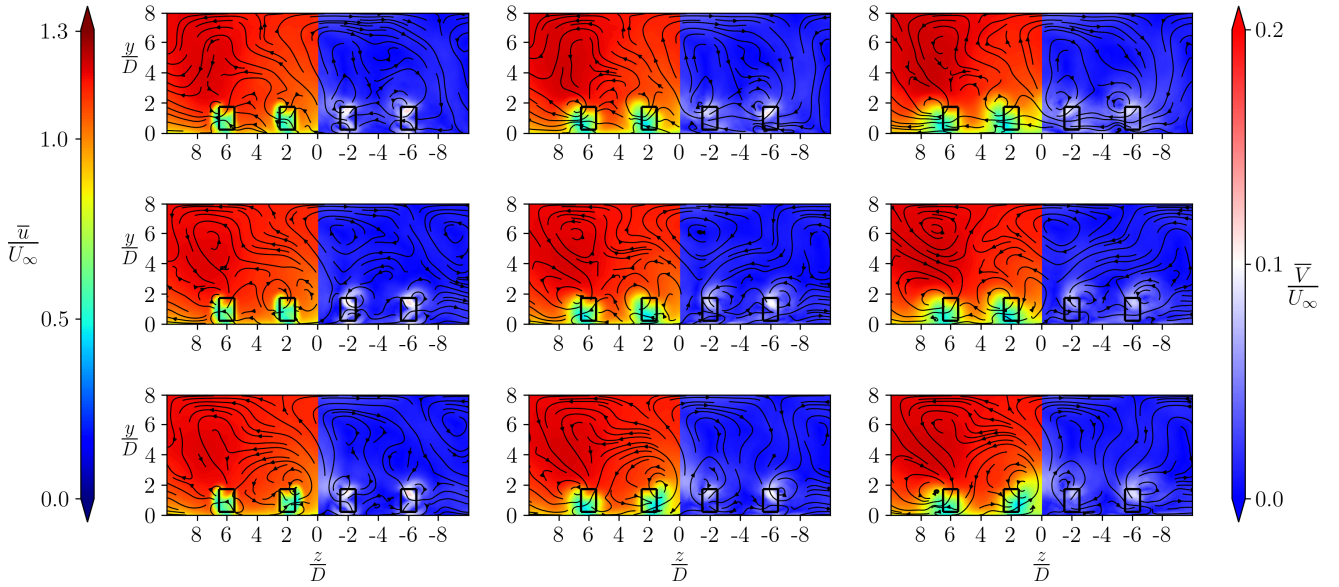
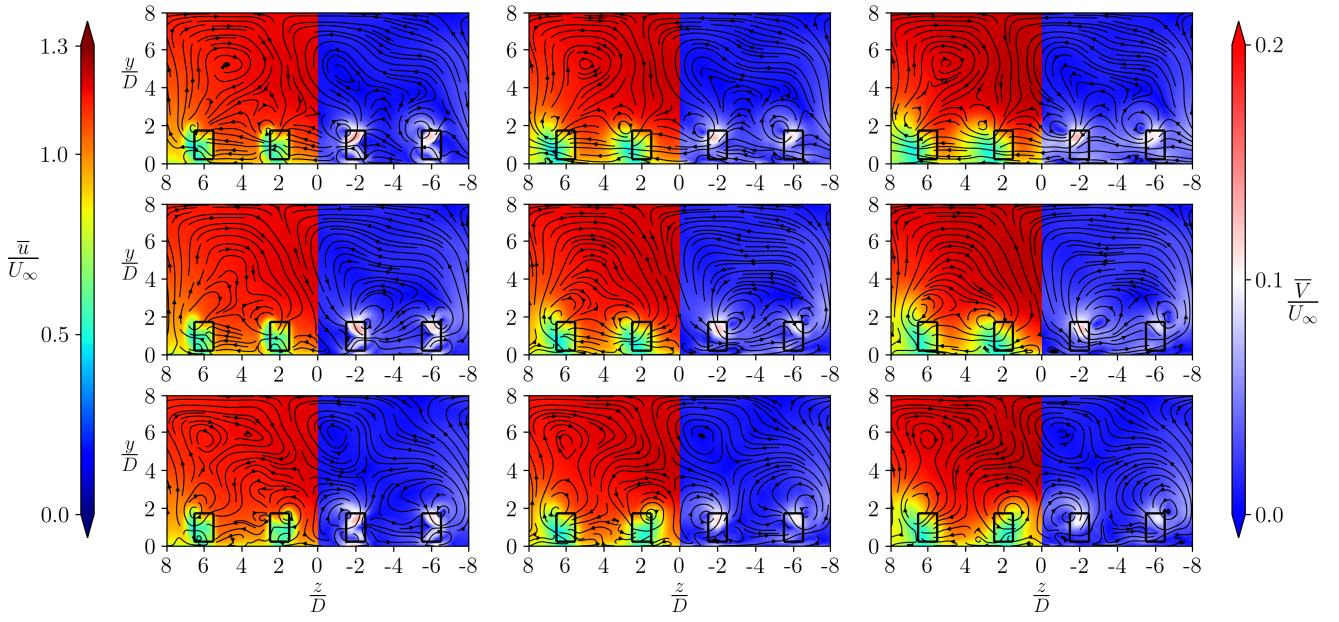


Figure 5.18: Time-averaged streamwise (left) and in-plane (right) velocity fields in cross section planes at different locations : 5D (left), 15D (center) and 25D (right) downstream of the first row. Every P4 configurations are represented : reference (top) the mirror (middle) and alternating (bottom) cases

Power available and recovery rate

In order to gain a better understanding of the flow characteristics at the rotor level, integral analyses are conducted at this specific height. The recovery of the wake can be characterized by the available power in the flow P and RR , the streamwise velocity recovery rate [24]. Those quantities are evaluated as functions of x and are given by:

$$P(x) = \left\langle \frac{\bar{u}^3(x)}{U_\infty^3} \right\rangle \quad RR(x) = \frac{D}{U_\infty} \left\langle \frac{\partial \bar{u}(x)}{\partial x} \right\rangle \quad (5.5.1)$$

Here, the operator $\langle \cdot \rangle$ represents spatial averaging. This averaging is performed over a rectangle centered with the farm with dimensions H by $16D$ and a normal vector aligned with the x axis. Since the direction of the wind does not matter for a vertical axis wind turbine the horizontal velocity $\sqrt{u^2 + w^2}$ is used instead of u for the computation of P . An equivalent velocity U_∞ is fixed to 11 m/s in order to obtain dimensionless values of P . This value is coherent with the ABL design and is also used to adimensionalize the wake recovery rate. The available power and wake recovery rate are then evaluated on cross-stream sections at every diameter along the x -axis.

Figures (5.19) present the evolution of the power while the figures (5.20) show the wake recovery rate within the wind farms for each blade pitch angle and rotation configurations.

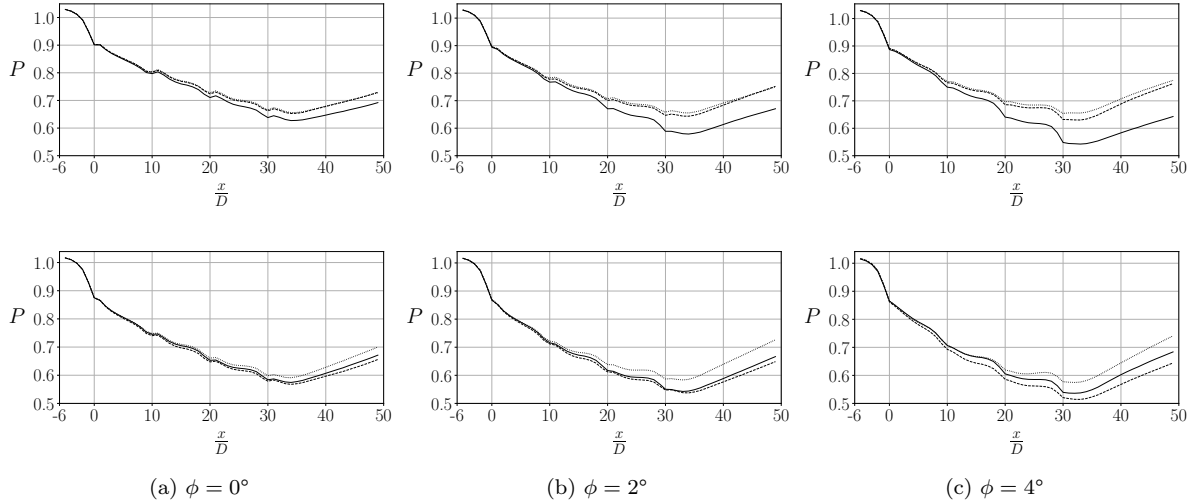


Figure 5.19: Available power in the flow in the infinite (top) and isolated (bottom) wind farms for every blade pitch setting from left to right : $\phi = [0^\circ; 2^\circ; 4^\circ]$. Rotation configuration are reference (solid), mirror (dashed), alternating (dotted)

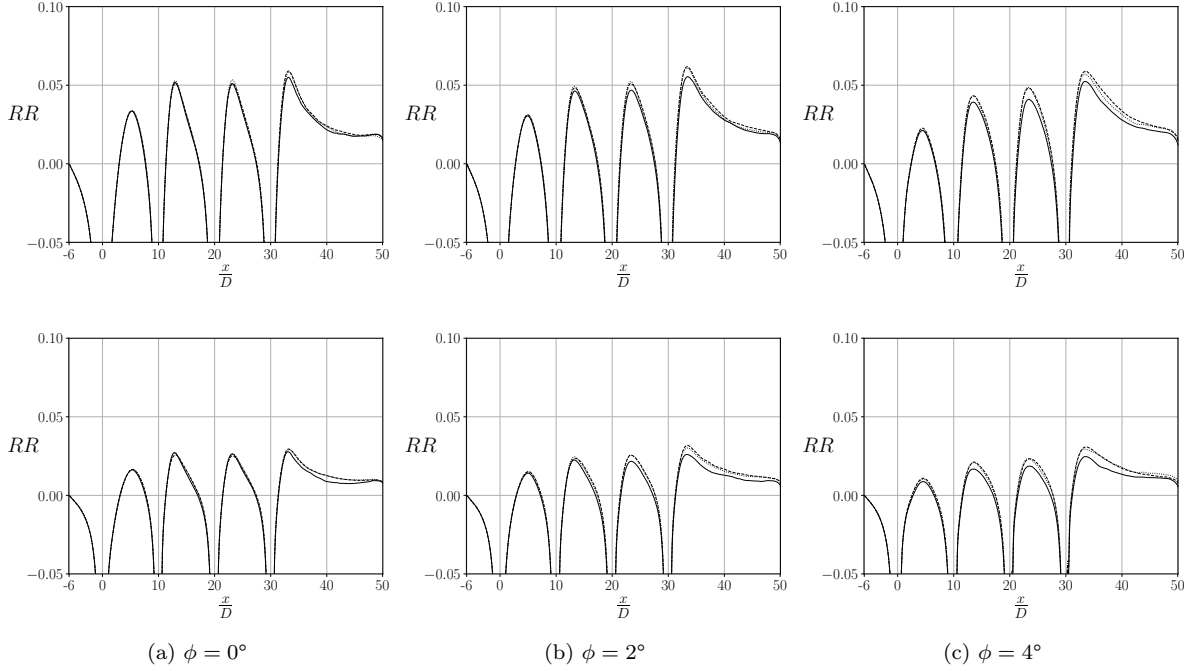


Figure 5.20: Wake recovery rate in the infinite (top) and isolated (bottom) wind farms for every blade pitch setting from left to right : $\phi = [0^\circ; 2^\circ; 4^\circ]$. Rotation configuration are reference (solid), mirror (dashed), alternating (dotted)

From the figures (5.19) and (5.20), several observations can be made upon the infinite wind farm scenario. Each row of VAWTs marks the power contained in the flow with a localized drop. Following the x axis, the available power progressively decreases within the wind farm. Past the farm, the resulting flow slowly re-energizes and its power rises.

Although every farm faces the same amount of available power, the reference farm tends to reduce this power more significantly as we move downstream within the farm. The mirror and alternating configurations present approximately the same available power curves with a higher amount of available power.

The power in the flow at the level of the VAWTs is either harnessed by the turbines or redirected vertically. According to the curves presented above, the drops in available power are slightly stronger in the reference scenarios. From this observation we can deduce that the turbines harvest more power using a reference configuration. This observation is further validated by the mechanical power output in tables (5.3).

The streamwise velocity recovery rate can help mitigate the drawbacks of the mirror and alternating scenarios. In all cases, the wake experiences short regions of positive acceleration between turbine rows. The P2 and P4 mirror and alternating configurations exhibit higher peaks in recovery rate, which results in a less abrupt decrease in available power between turbine rows. The difference from the reference case becomes more pronounced as we move downstream in the wind farm. This is due to the increasing influence of secondary flows generated by the rotation settings, which enhance downward motion. This motion impacts both the streamwise velocity recovery and the power available at the level of the

rotors. Past the farm, the recovery rate of the P4 setups is noticeably higher with mirror and alternating rotation direction.

The results for an isolated wind farm are slightly more varied. When examining the wake recovery rate, the isolated wind farm exhibits behavior similar to that of an infinitely wide wind farm. However, the intensity of the positive recovery of streamwise velocity is reduced by a factor of 0.5. This lower recovery rate can be correlated with the available power profile. Indeed, compared to the power available in the flow of the infinite wind farm, the power in the isolated wind farm is consistently lower. This lower power level accounts for the diminished recovery observed in the wake of the isolated farm.

The power within the flow in the isolated mirror scenario exhibits different behavior compared to the infinite case. In the infinite scenario, the power profile closely resembled that of the alternating case. However, in the isolated wind farm layout, the power available in the mirror case is even lower than in the reference case. This discrepancy can be explained by the absence of pronounced downward secondary flows in the velocity fields of the mirror case.

In both the reference and mirror cases, the lack of consistent vertical fluid motions within the farm does not effectively drive the wake away from the farm. Consequently, the integral analysis, which only accounts for the level of the VAWTs, shows a lower power level compared to the alternating case. In the alternating scenario, part of the velocity deficit is directed upward, contributing to higher power levels.

Additionally, the computation of available power incorporates the lateral velocity w . As a result, the reference scenario displays a slightly higher power profile, benefiting from the secondary lateral flow present in that configuration.

5.5.2 Kinetic energy

In order to observe and quantify the effects of the rotation configuration on the flow re-energizing at the turbines level, the dimensionless mean kinetic energy of the flow can be evaluated along the height of the domain.

$$\overline{K}(y) = \left\langle \left(\frac{\overline{u^2} + \overline{v^2} + \overline{w^2}}{2U_\infty^2} \right) \right\rangle \quad (5.5.2)$$

The operator $\langle \cdot \rangle$ corresponds to a spatial averaging over a horizontal plane of dimension $16De_z \times 30De_x$. This plane covers the farm from the first row to the last one. In the case of an isolated wind farm, the horizontal plane position is identical to its location in the infinite case. A velocity of $U_\infty = 11$ m/s is used to make the kinetic energy dimensionless. The figures hereunder, depict the evolution of the mean kinetic energy of the flow with respect to the height in the infinite wind farm scenario. The level of the VAWTs is visualized through the grey rectangle.

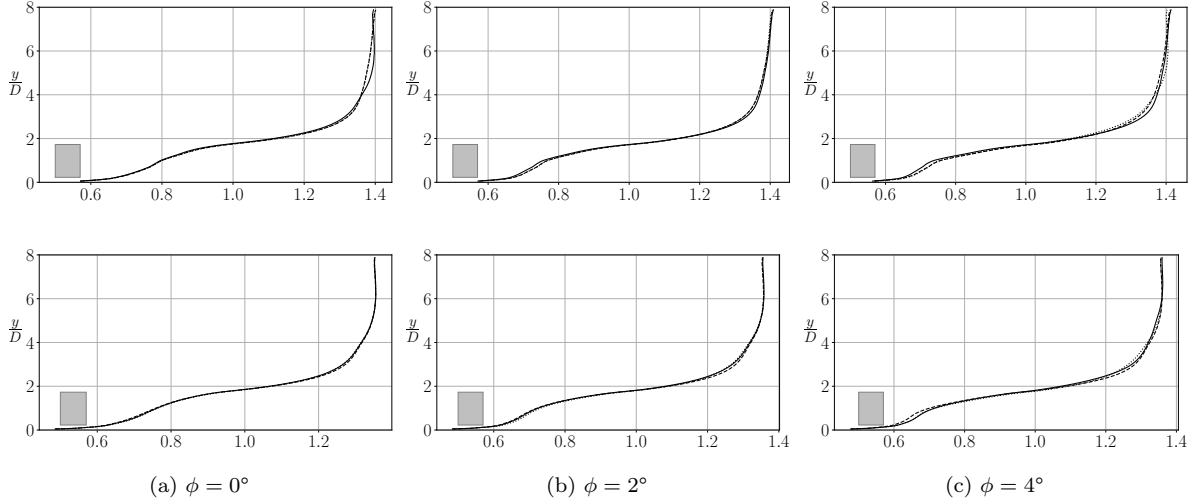


Figure 5.21: Time-averaged dimensionless kinetic energy $\overline{K}(\frac{y}{D})$ in the infinite (top) and isolated (bottom) wind farms for every blade pitch setting from left to right : $\phi = [0^\circ; 2^\circ; 4^\circ]$. Rotation configuration are : reference (solid), mirror (dashed), alternating (dotted).

It can be observed in the figures (5.21) that in the infinite wind farm, using the VAWTs in the mirror or alternated configuration progressively shifts the distribution of kinetic energy along the vertical direction. The high amount of kinetic energy present at high altitudes is decreased and brought down to the benefit of the lowest sub-layers. This effect, although small, is more and more visible as the blade pitch angle setting is increased inward.

Some differences are also noticeable between the mirror and alternating configurations. While the two rotation configurations exhibit approximately the same amount of kinetic energy at the rotors level, the origin of the gain differs. In the case of the alternating configuration, the energy seems to be taken from the layer $\frac{y}{D} \in [2; 3]$. We can see that in the case of the mirror configuration, higher levels of the atmospheric boundary layer are impacted.

In the case of an isolated wind farm, the transport of kinetic energy is even less pronounced, and the differences between the three rotational configurations are minimal. The only notable observation is a slightly reduced amount of energy at the level of the rotors in the mirror P4 scenario.

Although, these differences are minimal, the transport of kinetic energy can be observed as the time-averaged flux of kinetic energy through a horizontal plane at a given height.

$$\Phi_K(y) = v \left(\frac{u^2 + v^2 + w^2}{2} \right) \frac{1}{U_\infty^3} \quad (5.5.3)$$

The figures (5.22) present a visualization of the vertical transport of kinetic energy across horizontal planes located at the rotor's top as well as 1 radius and 1 diameter above the top of each VAWT for each P4 rotation configurations.

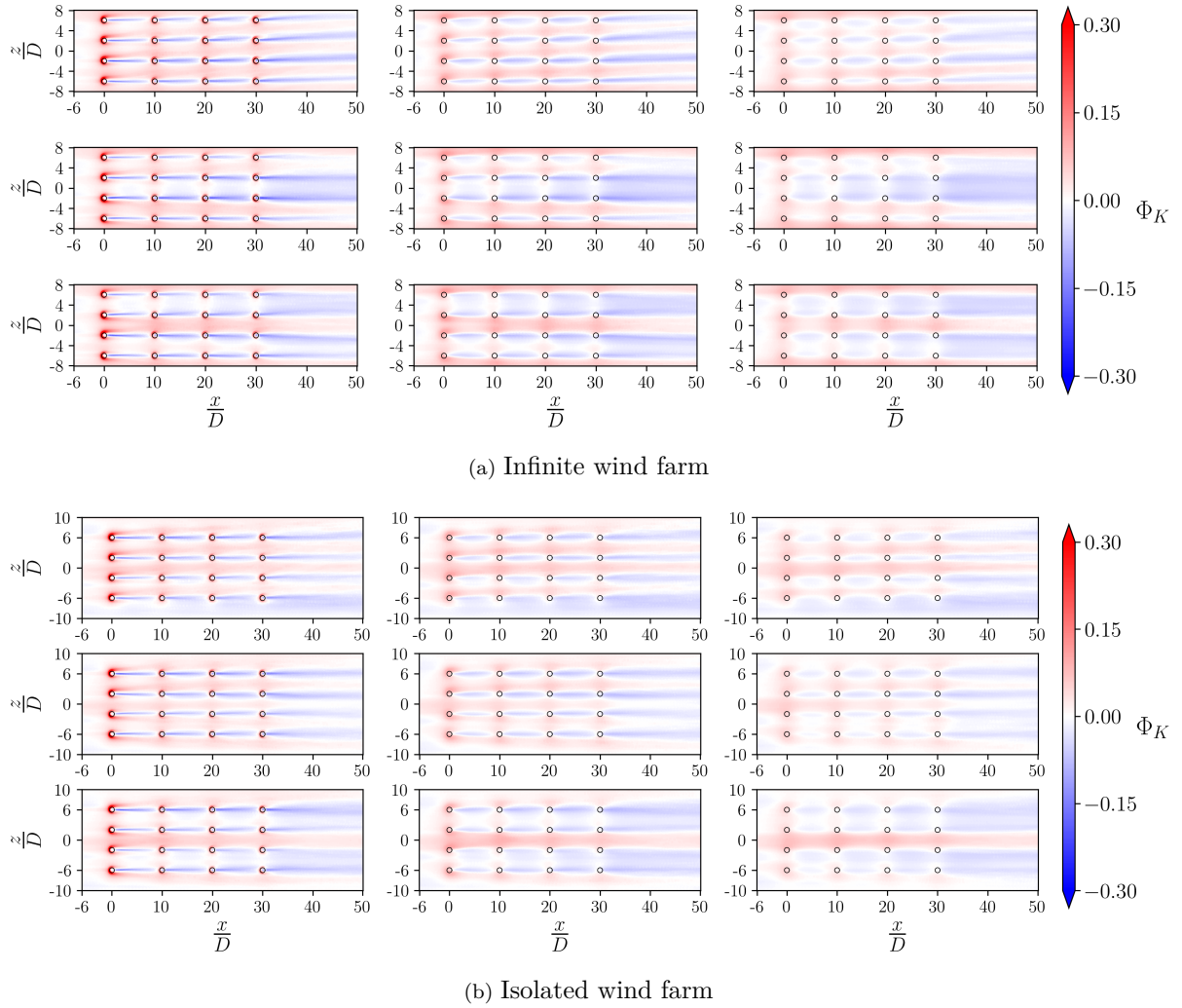


Figure 5.22: Time-averaged kinetic energy flux Φ_K in the infinite (top) and isolated (bottom) wind farms in every P4 rotation configuration across horizontal planes located : rotor's top (left) 1 radius (center) 1 diameter (right) above the top of the rotors. The rotation configurations are : reference (top) mirror (middle) alternating (bottom)

In every rotation configuration, the blockage effect caused by every row of the farm is clearly visible from the vertical redirection of fluid. Indeed, upstream of each row, an upward flux of energy is noticeable especially at the rotors top. The intensity of this flux progressively fades with the altitude.

Behind each rotor, we can see that the flux of energy forms concentrated channels of downward flux surrounded by upward motion of fluid. Those structures are explained by the vortex system created by the actuator cylinder. The latter generates downward as well as upward motion at its tips inherently from the creation of lift.

In the infinite reference scenario, these channels stay apart from each other and show only weak interactions in the far wake 1 radius to 1 diameter above the wind farm's top. On

the other hand, the same channels generated in a mirror or alternating configuration seem to merge in pair to form wider channels. In the mirror scenario, all the channels eventually merge into a global downstream current in the far wake 1 diameter above the wind farm.

Furthermore, it can be observed that in the mirror setup, the rotor lines at $\frac{z}{D} = \pm 6$ do not benefit as much from the downstream secondary flow as the central lines, due to their position. In fact, looking at the power output distribution within the downstream lines of the infinite farm under uniform inflow conditions in figure (C.1a), the center lines show greater mechanical power than the side ones under uniform inflow conditions. This imbalance of also exists within the farm under ABL conditions. However, since the imbalance differs between the infinite and isolated cases, it is most likely explained by the presence of long structures within the ABL.

The isolated wind farms exhibit several differences compared to the infinitely wide configurations. Firstly, the mirror-configured farm does not demonstrate the same interactions between channels of downward energy flux. The turbine lines appear to work in a more individualistic manner. The same observation is also visible in the reference scenario. The latter presents also a large region of downward kinetic energy transport for $z < -6D$. Indeed, at the side of the farm, the flow gets aspirated downward as visible in figure (5.18b).

In the alternating scenario, two merged channels remain observable, separated by a strong upward flux. The maintenance of the secondary flow structure in the alternating configuration may be attributed to the lower periodicity of the rotation setup within a row.

Finally, as observed in the velocity fields at mid-span, the isolated farm did not exhibit the same degree of wake deflection than the infinite scenario. The wake-turbine interactions are slightly more present within the farm. Since the VAWTs rows face more the velocity deficit, the blockage induced by the turbine has less impact on the vertical redirection of the flow just upstream of each turbine. Thus, the peak in energy flux that were present in the infinite wind farm cases appear slightly reduced in the case of an isolated wind farm.

The previously introduced¹ operator $\langle \cdot \rangle$ is then applied to the vertical flux of kinetic energy to have an better idea of the strength of the exchanges between sublayers. These values are computed for each wind farm configurations at 3 different heights and presented on figures (5.23a) and (5.23b) for the infinitely wide and isolated cases.

¹In the frame of kinetic energy computation

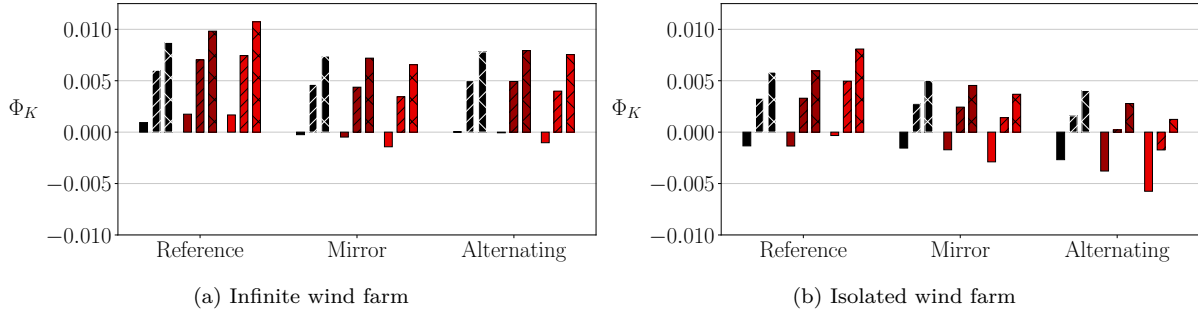


Figure 5.23: Mean kinetic energy flux across horizontal planes located : 0 radius (unfilled), 1 radius (hatched), 2 radius (cross-hatched) above the top of the rotor. The colors of the bars relate to the pitch setup : P0 (black), P2 (dark red), P4 (red)

The bars presented above indicate the farm's capacity to either increase or decrease the useful kinetic energy at the level of the turbines. In every case, the mean kinetic energy flux increases as we measure it higher. Combined with the observations in figures (5.18a) and (5.21), this increase is attributed to the shape of the ABL velocity profile rather than an intensification of the vertical velocity at this height.

In the infinite wind farm scenarios, the mirror and alternating configurations exhibit mean fluxes $\Phi_K < 0$, indicating that at the level of the turbine tops, kinetic energy is slightly transported downward. These negative mean fluxes change sign at higher altitudes. Conversely, in the reference scenario, kinetic energy in the flow is expelled from the farm. Positive values of mean kinetic energy flux are observed as soon as we move above the rotors.

Moreover, the mean energy flux values are generally lower in the mirror and alternating configurations compared to the corresponding reference scenario. This reduction is likely due to secondary flows bringing more energetic fluid toward the turbines.

Additionally, the mean kinetic energy flux is generally lower in the mirror configurations compared to the alternating configurations. As shown in figure (5.23a), the mirror setup exhibits slightly stronger patches of negative flux values within the farm, and the regions of upward flux, which are confined to the sides of the wind farm, have less impact on the mean flux than in cases where a central region of upward flux is also present.

In the isolated wind farm, the results are more mixed. First, the intensity of the mean flux reaches significantly lower values, with even more negative values, compared to the infinite farm. As previously observed, this difference can be attributed to the lower intensity of the vertical velocity peaks observed near the upstream part of each rotor, leading to a reduction in the mean flux values.

Finally, as the blade pitch setting is increased, the energy fluxes in the reference configuration show an increase, whereas in the mirror and alternating configurations, these fluxes decrease. This trend is particularly evident in the alternating scenario, where the flux values turn negative even at a height of one rotor radius above the turbine tops. This indicates that, despite the isolated nature of the wind farm, the mirror and alternating configurations still exert a degree of control over the atmospheric boundary layer.

5.5.3 Power

Following the analysis made with the uniform inflow, we consider a 4 by 4 VAWTs section of the infinitely wide wind farm. The total power production in MW of the infinite and isolated farms are respectively gathered below in tables (5.3) and (5.4). For each wind farm, the gain or loss are computed with respect to the P0 reference case of the corresponding wind farm. The detailed distribution of the power output within the farms are presented in appendix (C) in figures (C.2a) and (C.2b).

	Reference	Mirror	Alternating
P0	41.2	41.1 (-0.3%)	40.3 (-2.2%)
P2	42.1 (+2.2%)	40.5 (-1.7%)	38.7 (-6.2%)
P4	37.0 (-10.2%)	34.9 (-15.3%)	32.9 (-20.3%)

Table 5.3: Infinite wind farm

	Reference	Mirror	Alternating
P0	37.9	36.8 (-3.0%)	37.7 (-0.5%)
P2	37.6 (-0.8%)	35.5 (-6.4%)	36.6 (-3.5%)
P4	31.6 (-16.8%)	30.5 (-19.6%)	31.3 (-17.5%)

Table 5.4: Isolated wind farm

First of all, the distribution of power output presented in appendix spread unevenly within a row of VAWTs. This phenomenon is partly explained by the presence of long and slim wind structures in the inflow observed earlier. On top of that, the infinite and isolated wind farm cannot be properly compared due to the differences observed in their respective ABL inflow.

It can be immediately noticed that in the results diverge from those observed under uniform inflow conditions. The installation shows a higher power coefficient when the blade pitch angle is fixed at zero compared to the uniform inflow case. As previously mentioned, in every P0 configuration, the second row of turbines in a uniform inflow scenario proves to be inefficient. However, in the ABL, the increased turbulence makes the second row significantly more effective due to stronger turbulent mixing and earlier wake recovery. This grants the farm of an additional row that couldn't be exploited in uniform inflow conditions.

An increase in the pitch angle, ϕ , significantly degrades the overall production of the farm. While it might be expected that the secondary flows formed could compensate for or even surpass the loss caused by increasing the pitch of the blades inward, this is not the case under ABL conditions. These secondary structures are not strong or organized enough to compensate for the loss due to the increased pitch angle. These losses are substantial and can reach up to 20% of the power generated by the reference P0 configuration.

Mirror and alternating setups once again show a lower power output than the reference cases, both within the infinite and isolated wind farms, for any blade pitch setting. This observation can be explained by the fact that the lateral wind generated in the reference configuration contributes to the power generation. While the vertical fluid motions generated in the mirror and alternating scenarios do not.

5.6 Conclusion

This final chapter aimed to observe the formation of secondary flows and assess their impact on atmospheric boundary layer control. The ultimate goal was to determine if controlling the ABL could increase the overall power density of the wind farm. The wind farm layout was investigated under two inflow conditions: uniform inflow with slip boundary conditions, and an atmospheric boundary layer profile inflow coupled with a wall model. Based on the periodic boundary conditions and the domain's width, the wind farm was considered either infinitely wide or isolated. Three rotation's direction setups were studied: a reference configuration and two customized configurations, named the mirror and alternating setups. Additionally, fixed blade pitch angles were introduced for each turbine in the farm.

In the uniform inflow cases, clear patterns of secondary flows emerged. In the case of the mirror and alternating setups, these patterns were composed of large vortex with substantial vertical velocity regions. The secondary flows were able to interact with higher levels of the flow, up to three to four diameters high. The reference case created a strong lateral current within the farm. Those patterns were also observed under the ABL inflow. However, they appeared weaker and not as coherent as the previous ones.

In the uniform inflow scenario, power production was optimal with a blade pitch setting of approximately 2° inward. However, this improvement cannot be attributed solely to the formation of secondary flows. Rather, it is primarily due to the introduction of blade pitch, which enabled the second row of turbines to generate power more effectively, as they were previously in the wake of the upstream turbines when operating with a zero blade pitch setting.

In the case of the atmospheric boundary layer inflow, analysis shown that there was indeed slightly enhanced exchanges of kinetic energy between the VAWT's level and higher altitudes in the mirror and alternating rotation configurations. However, the contribution of these exchanges was not as strong as expected and the simple lateral wind created by the reference rotation setup contributed more to the increase of the power density of the farm. In the case of the ABL, the wind farm generally exhibits lower power outputs.

Chapter 6

Conclusions and perspectives

This thesis was undertaken to prove if the concept of atmospheric boundary layer control through vertical axis wind turbine with given blade pitch angle and rotation setup could improve the power density of offshore wind farms.

The first part of the thesis assessed the ability of a single wind turbine to deflect the wake sideways under uniform and logarithmic velocity profile inflows. It was shown that the introduction of a fixed blade pitch enhanced the production of lateral force, with inward pitch settings proving to be the most efficient way to achieve this deflection. However, the introduction of a fixed blade pitch angle also decreased the mechanical power generated by the turbine. A 2° blade pitch was found to be the ideal trade-off between lateral force and power generation.

In Chapter 4, the impact of the streamwise distance between two aligned rotors on their power output and lateral force generation was investigated. Several inter-distances were tested simultaneously with inward pitch settings under uniform inflow. As a result, in configurations with a low pitch setting, the downstream turbine experienced significant power loss due to the wake of the upstream one. Increasing the pitch enhanced the production of the downstream turbine. However, setting the pitch too high inward reduced the power output of both turbines. A blade pitch setting between 2° and 3° for an inter-distance of 10 diameters was found to be the optimal trade-off. This distance was chosen as the basis for the farm layout of the next chapter.

Finally, VAWTs were placed in a wind farm layout and simulated for several rotation and blade pitch angle setups. Two types of wind farms were assessed: an infinitely wide farm and an isolated one. The latter were studied under uniform inflow and atmospheric boundary layer (ABL) inflow conditions. The objective of this final chapter was to demonstrate the formation of secondary flow structures and assess their effect on turbine production. Very interesting results were found regarding the generation of secondary flows. Indeed, in the three rotation configurations investigated, substantial lateral as well as vertical fluid motions were observed. The vertical secondary flows were promising as they contribute to bringing down the upper layers of the flow, which have more energy, to the level of the turbine while expelling the rotor wakes upwards. These exchanges were assessed through integral analysis and kinetic energy fluxes. However, it was found that these

exchanges were not strong enough to compensate for the losses due to blade pitching and wake-turbine interactions within the farm.

This thesis demonstrates that, within a vertical axis wind turbine farm, a certain level of control can be achieved on the higher altitudes of the boundary layer, and kinetic energy exchanges can be enhanced through the farm's rotation configuration. The farm layouts simulated in this work did not substantially benefit from these exchanges. However, it sets the stage for further research by opening up several new perspectives. Other setups could be tested, and an optimal configuration that benefits from these large secondary flows could potentially be found through an iterative process that individually modifies the positioning of the turbines relative to each other (new streamwise or transverse inter-distances, staggered distribution, ...), the rotation direction, and the blade pitch settings to maximize the farm's power density. A heterogeneous blade pitch setting within the farm could be envisioned, where part of the farm is designed to control the ABL while other turbines are optimized to harvest this added power in the most effective configuration.

Appendix A

Striped wake issues investigation

Using the actuator cylinder model developed at UCLouvain in a uniform flow, the wake presents in some cases stripes structures which does not seem physical. Those lines also appears in other previous master thesis that used the actuator cylinder method such as [19] [30] [20] and [3]. Every blade pitch configuration $[-5^\circ; 5^\circ]$ present stripes in their wake. These stripes are nevertheless more visible in the case of inward blade pitch. The figure below presents the time-averaged streamwise velocity in configurations with 0° and 5° inward blade pitch.

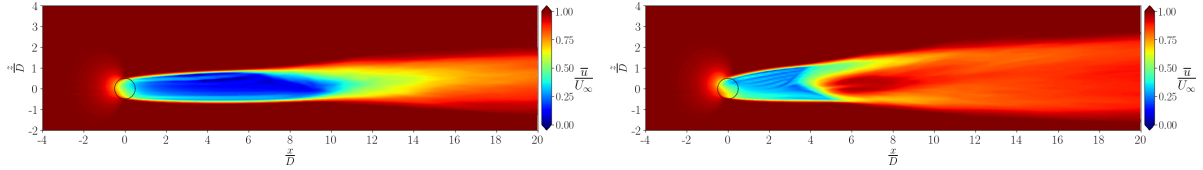


Figure A.1: Time averaged normalized streamwise velocity $\frac{\bar{u}}{U_\infty}$ on mid-span plane for both pitch configurations

The striped structures are mostly located on each side of the wake but propagate toward the hole mid-span wake with an inward fixed blade pitch. The 5° inward blade pitch case is study in this investigation since the intensity of the phenomenon is more visible in those conditions. The main parameters of the reference case are gathered in the table hereunder.

VAWT		Domain & Simulation	
Method	ACM	(nDx, nDy, nDz)	(24, 10, 10)
H/D	138/92 [m]	pts/D	16 (no stretching)
$(x, y, z)_{\text{center}}$	(368, 391, 460) [m]	B.C x+/x-	Dirichlet
Nr/Ntheta	24/62	B.C y+/y-	Slip
rpm	9.19	B.C z+/z-	Periodic
Pitch	5° inward	CFD scheme order	4
Polar	NACA0015 $\text{Re} = 10^7$ [28]	Δt	0.05
Dynamic stall	ON	nt	8360
Control	OFF	Poisson solver residual	10^{-5}
DistribType	M4	StatsBufferSize	4180

Table A.1: Main parameters of the reference case

In order to reduce the stripe effect, 4 path were explored one by one.

- Reducing the tolerance on the residual of the poisson solver to 10^{-7}
- Using a 2^{nd} order spatial integration scheme
- Increase to 100 the number of points on the azimuthal direction of the VAWT
- Modifying the mollification for a 3D gaussian type with a $2\Delta h$ standard deviation.

For each case, the streamwise time-averaged normalized velocity is plotted below on a mid-span cross section. The velocity is averaged over 4180 iterations.

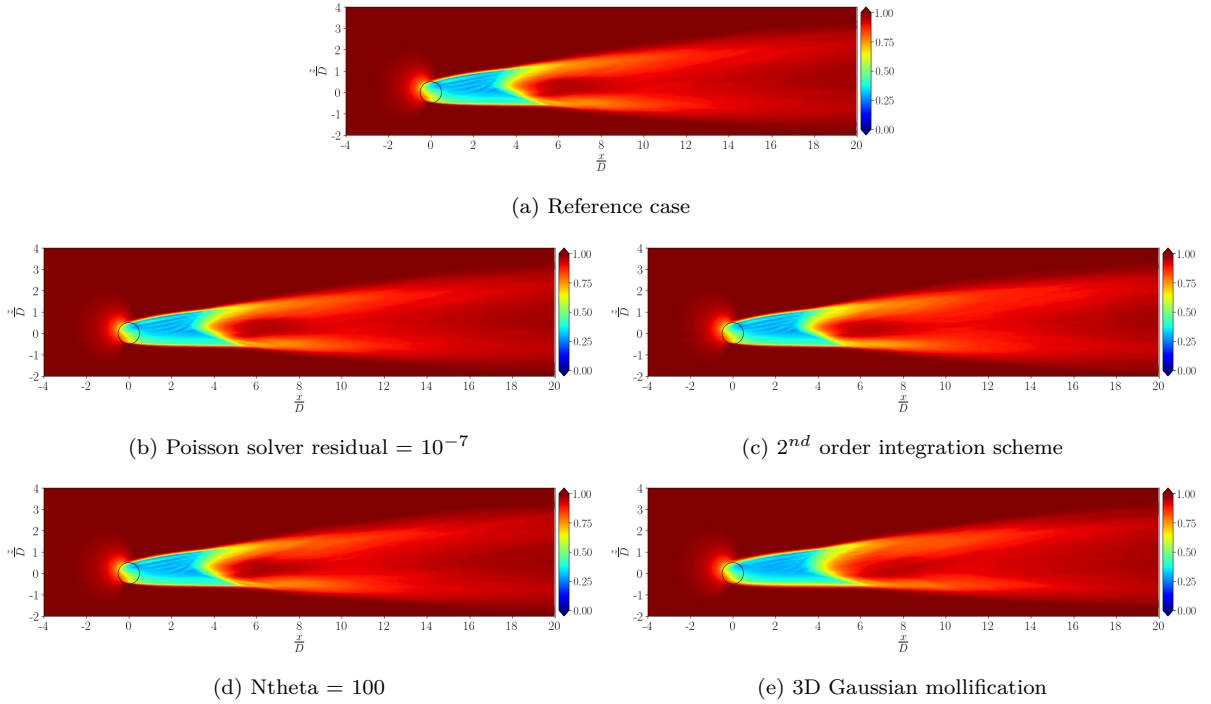


Figure A.2: Time averaged normalized streamwise velocity $\bar{u}/U_\infty$ on mid-span plane for both pitch configurations

Only the modification of the mollification seems to have an efficient impact over the presences of the structures. A standard deviation of $3\Delta h$ is thus also simulated. This distribution give the following wake.

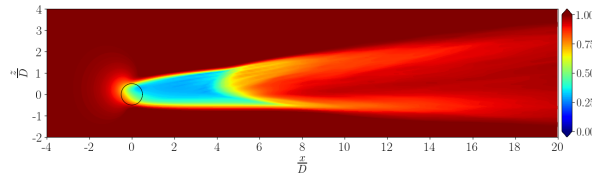


Figure A.3: 3D gaussian mollification with $3\Delta h$ standard deviation

Next figures present the angle of attack, the normal and tangential force over a rotation. Those quantities are taken at mid-span and are averaged over 5 rotations. Given the rpm and the dt, the average is made over the last 665 iterations.

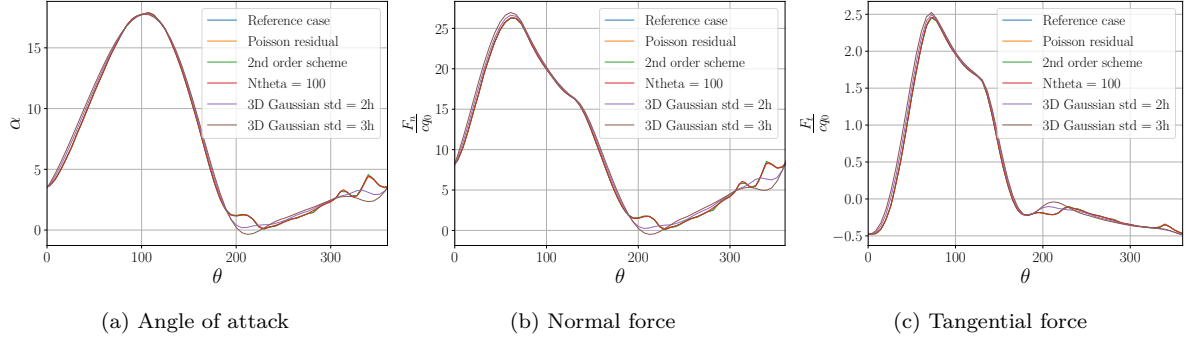


Figure A.4: Diagnostics at mid-span

Every investigation path shows approximately the same behavior in the upstream part of the VAWT i.e., $\theta \in [0^\circ; 180^\circ]$. Changing the mollification seems to be the only path that really changes the downstream diagnostics. The peaks observed for the $\theta \in [300^\circ; 360^\circ]$ are smoothed out. Exploring more deeply this investigation could lead to interesting results. Nevertheless, spreading to much the 3D gaussian could end up in not physical results

However, comparing the power output between the reference case and the gaussian distributions with $2\Delta h$ and $3\Delta h$, the steady power coefficients are respectively 0.2795, 0.3097 and 0.3367. This difference is not negligible, the choice is then made to keep using the reference case for study in the frame of this TFE.

Appendix B

Double rotor : Lateral force and power coefficients

Hereunder are gathered the lateral force and power coefficients of the double wind turbine study for every turbine inter-distance x_{sep} and blade pitch angle ϕ considered. The upstream turbine is indexed as 1, and the downstream turbine as 2. These coefficients are averaged over the last 50 dimensionless time of the simulation which has been running for 33440 time steps at $\Delta t = 0.05$ s.

	Single	$x_{sep} = 4D$		$x_{sep} = 6D$		$x_{sep} = 8D$		$x_{sep} = 10D$	
		$C_{z,1}$	$C_{z,2}$	$C_{z,1}$	$C_{z,2}$	$C_{z,1}$	$C_{z,2}$	$C_{z,1}$	$C_{z,2}$
$C_z(\phi = 0^\circ)$	0.128	0.128	0.004	0.128	0.001	0.128	0.002	0.128	0.007
$C_z(\phi = 1^\circ)$	0.178	0.178	0.007	0.178	0.005	0.178	0.003	0.178	0.021
$C_z(\phi = 2^\circ)$	0.229	0.229	0.006	0.229	0.002	0.229	0.023	0.229	0.075
$C_z(\phi = 3^\circ)$	0.280	0.278	-0.004	0.279	0.001	0.280	0.065	0.280	0.132
$C_z(\phi = 4^\circ)$	0.328	0.327	0.0001	0.328	0.008	0.328	0.123	0.328	0.188
$C_z(\phi = 5^\circ)$	0.370	0.368	-0.023	0.369	0.069	0.370	0.160	0.370	0.223

Table B.1: Time-averaged lateral force coefficients C_z for each blade pitch angle and turbine separation distance.

	Single	$x_{sep} = 4D$		$x_{sep} = 6D$		$x_{sep} = 8D$		$x_{sep} = 10D$	
		$C_{P,1}$	$C_{P,2}$	$C_{P,1}$	$C_{P,2}$	$C_{P,1}$	$C_{P,2}$	$C_{P,1}$	$C_{P,2}$
$C_P(\phi = 0^\circ)$	0.3943	0.391	0.003	0.394	0.004	0.394	0.003	0.394	0.031
$C_P(\phi = 1^\circ)$	0.391	0.388	0.005	0.390	0.002	0.391	0.005	0.391	0.125
$C_P(\phi = 2^\circ)$	0.382	0.381	0.003	0.381	0.007	0.381	0.146	0.381	0.227
$C_P(\phi = 3^\circ)$	0.363	0.362	0.003	0.361	0.142	0.362	0.222	0.363	0.249
$C_P(\phi = 4^\circ)$	0.332	0.327	0.104	0.329	0.175	0.331	0.209	0.332	0.231
$C_P(\phi = 5^\circ)$	0.281	0.276	0.111	0.279	0.155	0.281	0.171	0.281	0.190

Table B.2: Time-averaged power coefficients C_P for each blade pitch angle and turbine separation distance.

Appendix C

Wind farms power coefficients

In this appendix, the power output of each turbine within the studied 4 by 4 wind farms are presented. The wind farm can be divided in 4 VAWT's lines aligned with the x-axis and 4 rows aligned with the z-axis. The lines 1, 2, 3 and 4 are respectively located at $z = [6D, 2D, -2D, -6D]$ and the row are located at $x = [0D, 10D, 20D, 30D]$. In the following figures the lines 1, 2, 3, 4 are respectively represented in brown, purple, red and green.

As expected from the chapter 4, P0 makes the second VAWT ineffective, P2 and P4 allow it to generate a certain amount of power at the cost of slightly reducing the output of the first turbines.

The uneven distribution of mechanical power within the rows of the wind farms under atmospheric boundary layer (ABL) inflow conditions is largely explained by the presence of long wind structures generated by the ABL formation process. Some lines that experience slightly higher wind velocities produce more power. Since the original ABL used to simulate behavior in an infinitely wide wind farm was assembled with itself to create a wider ABL for investigating isolated cases, the uneven power distribution differs between the infinite and isolated farms. This variation is due to their different transverse positions within the same ABL.

Wind farm with uniform inflow

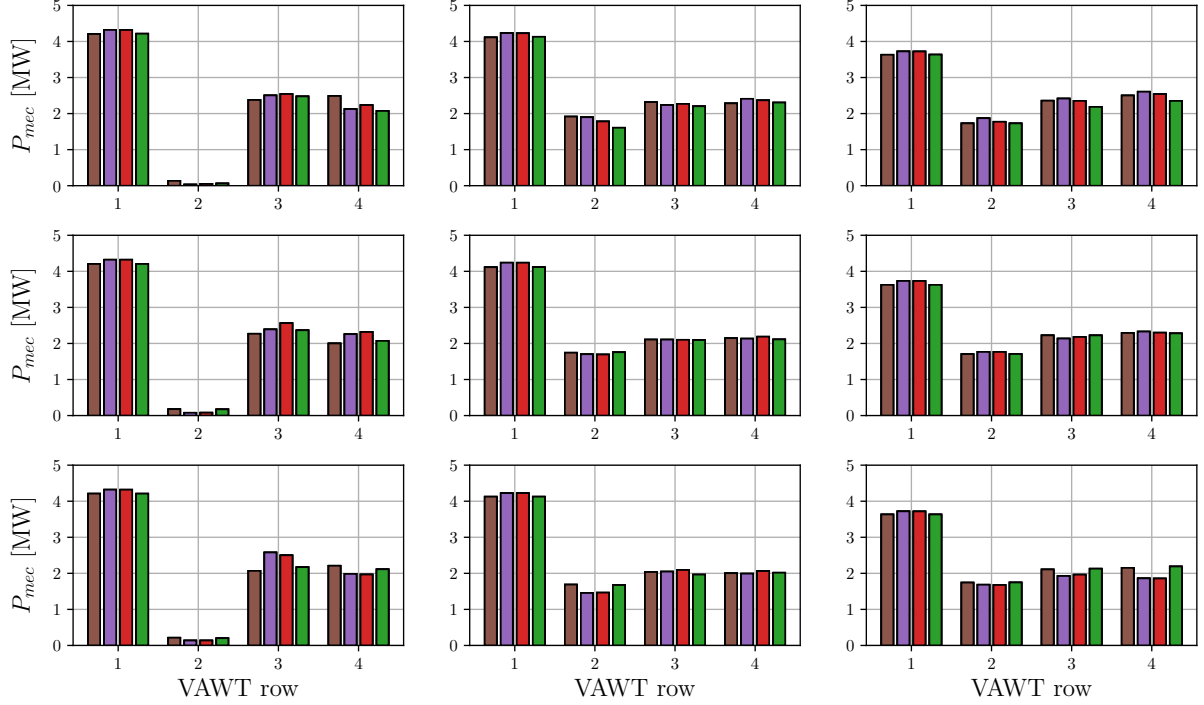
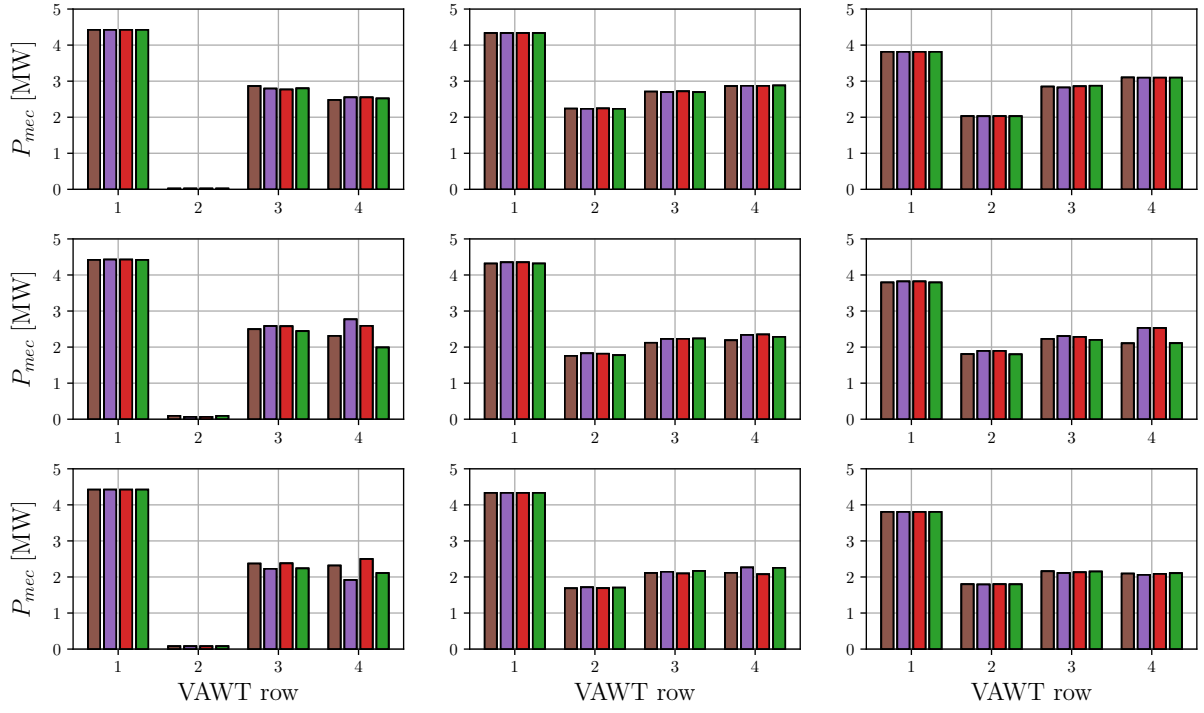
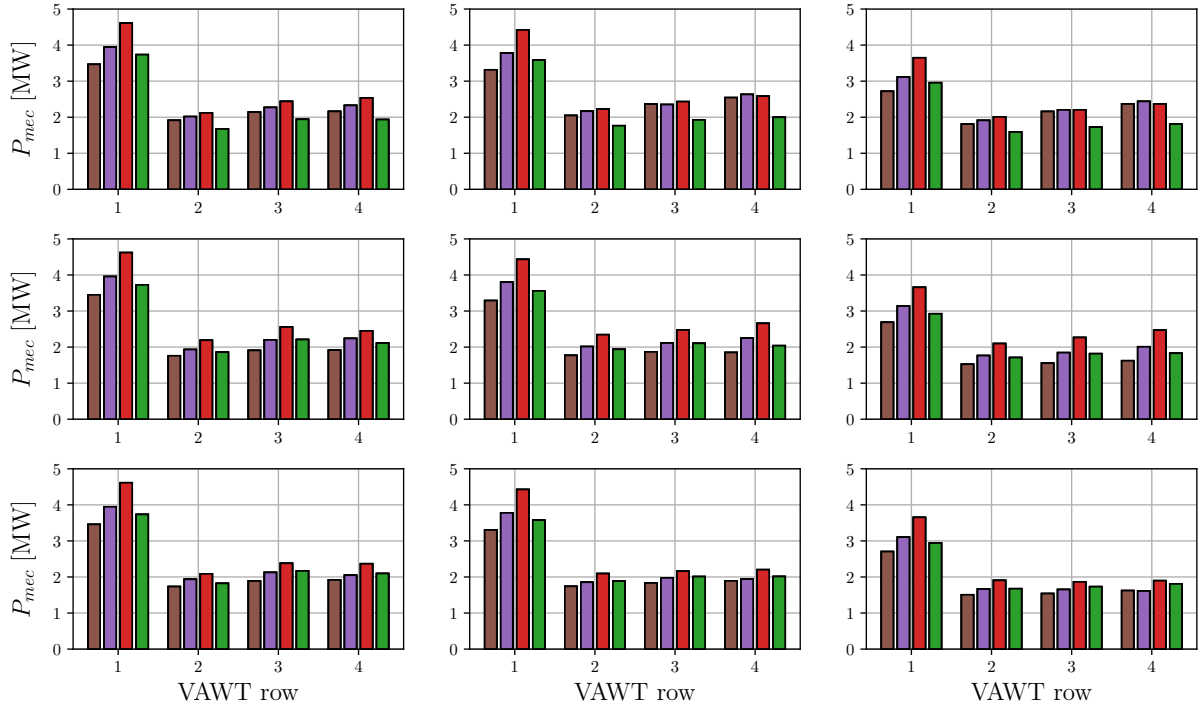
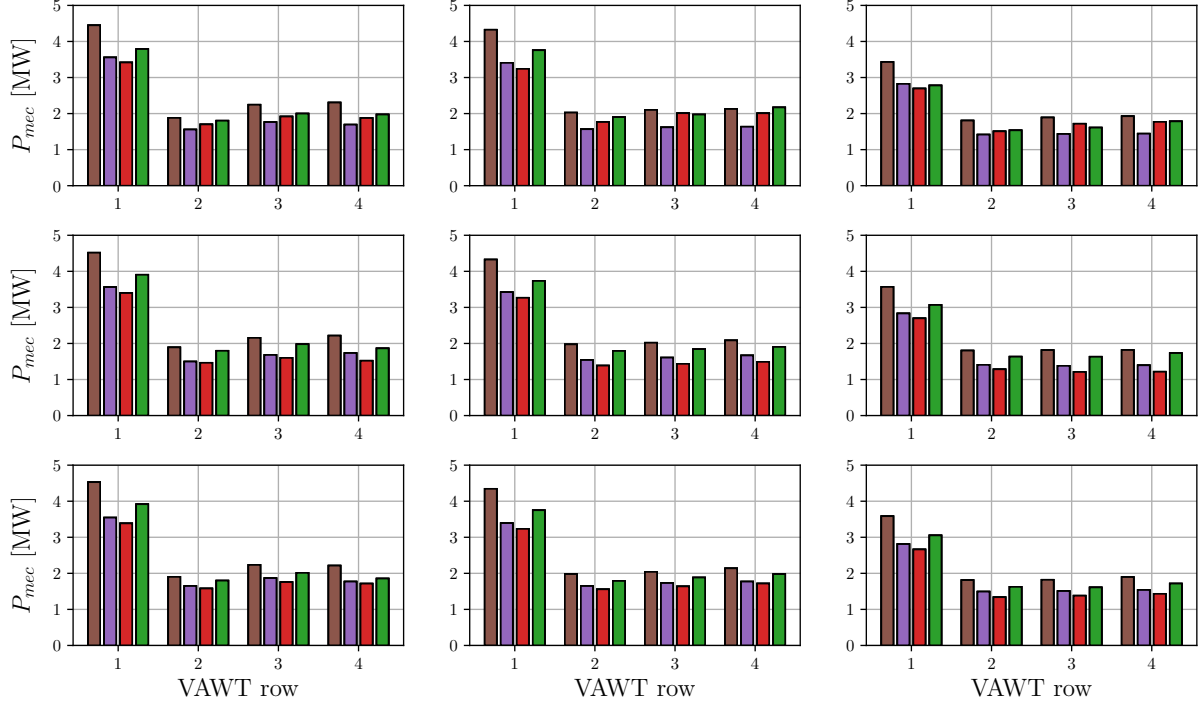


Figure C.1: Time-averaged power distribution within the wind farms for every rotation configuration : Reference (top), Mirror (middle), Alternating (bottom) and for every blade pitch angle : P0 (left), P2 (center), P4 (right)

Wind farm within an atmospheric boundary layer



(a) Infinitely wide wind farm



(b) Isolated wind farm

Figure C.2: Time-averaged power distribution within the wind farms for every rotation configuration : Reference (top), Mirror (middle), Alternating (bottom) and for every blade pitch angle : P0 (left), P2 (center), P4 (right)

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