

École polytechnique de Louvain

Investigation of wind turbine wakes subjected to helicoidal perturbations

Author: **Tristan RICHARD**

Supervisor: **Philippe CHATELAIN, Matthieu DUPONCHEEL**

Reader: **Hervé JEANMART**

Academic year 2024–2025

Master [120] in Mechanical Engineering

Abstract

Wind farms, despite their advantages, face a major challenge. As the first row of turbines extracts energy from the flow, it generates a region of reduced velocity downstream, referred to as the wake. This significantly limits the power production of downstream turbines, reducing the overall efficiency of the wind farm. To mitigate this effect, helix control strategies use individual pitch control (IPC) to create a rotation of the thrust application point around the rotor center, either in a clockwise (CW) or counter-clockwise (CCW) direction, giving the wake a helicoidal shape.

While the effectiveness of helix control has been demonstrated in many studies, the physical mechanisms underlying its performance remain not fully understood. This Master's thesis aims to fill this gap using Large Eddy Simulations combined with a simplified force model. The analysis shows that IPC-induced normal force produces an uneven velocity deficit in the wake. This deficit generates induced velocities, which in turn trigger specific flow mechanisms that result in the formation of a counter-rotating vortex pair (CVP) in both helix. This CVP appears to explain the improved performance of helix control through two effects: a radial deflection of the wake and an accelerated recovery of the velocity deficit. We observe an interaction between the swirl and the CCW helix, leading to a different CVP orientation compared to the CW case, which could explain the better performance of the CCW helix.

Acknowledgment

This work marks the conclusion of five wonderful years at EPL. I have learned so much during this time, although the journey was not always easy. First, I would like to thank my parents, brother, girlfriend, and friends for their unwavering support throughout this path.

Next, I want to sincerely thank Professor Philippe Chatelain and Professor Matthieu Duponcheel for giving me the opportunity to work on such a fascinating subject. Their expertise, guidance, and advice throughout the year have been extremely insightful. I am also very grateful to Dr. Marion Coquelet and Dr. Maud Moens, whose generous help and constant availability were invaluable throughout the entire process. I would also like to thank Sébastien and my parents for their help with proofreading. Finally, I extend my gratitude to Professor Hervé Jeanmart for kindly agreeing to be part of the jury.

I would also like to pay tribute to my high school teacher, Professor Claude Delforge, who instilled in me the passion for mathematics and engineering.

Computational resources have been provided by the supercomputing facilities of the Université catholique de Louvain (CISM/UCL) and the Consortium des Équipements de Calcul Intensif en Fédération Wallonie Bruxelles (CÉCI) funded by the Fond de la Recherche Scientifique de Belgique (F.R.S.-FNRS) under convention 2.5020.11 and by the Walloon Region. ChatGPT has been used for grammatical correction and syntax improvement.

Contents

Abstract	i
Acknowledgements	ii
Contents	iv
List of Figures	v
List of Tables	ix
List of Abbreviations	x
1 Introduction	1
1.1 Foreword	1
1.2 Scope of the work and literature review	2
1.3 Objectives	4
1.4 Outline	5
2 Methodology	6
2.1 Flow solver	6
2.2 Wind turbine modelling	8
2.3 Controllers	12
2.4 Numerical setup	15
3 Numerical improvements to clarify the wake dynamics	16
3.1 Modelling of wind turbine aerodynamic forces	16
3.1.1 Normal force modelling	16
3.1.2 Tangential force modelling	25
3.1.3 Additional features for enhanced numerical stability	31
3.2 Effect of the force approximation model on wake dynamics	32
3.2.1 Baseline control	33
3.2.2 Static offset control	35

3.2.3	CW helix control	36
3.2.4	CCW helix control	37
4	Investigation of wake dynamics	38
4.1	Baseline control	38
4.2	Static offset control	40
4.2.1	Near wake region	41
4.2.2	Mid wake region	42
4.2.3	Far wake region	43
4.3	CW helix control	44
4.3.1	Near wake region	45
4.3.2	Mid wake region	46
4.3.3	Far wake region	47
4.4	CCW helix control	48
4.4.1	Near wake region	48
4.4.2	Mid wake region	49
4.4.3	Far wake region	50
4.5	Influence of the tangential force	51
4.6	Performance assessment	55
5	Conclusion	57
5.1	Discussion	57
5.2	Perspectives	58
	Appendices	59
A	Domain size optimisation	59
B	Influence of tangential force in CW helix	61

List of Figures

1.1	Horns Rev 1 offshore wind farm property of Vattenfall - Photographer Christian Steiness.	2
2.1	Illustration of a wind turbine showing the forces and moments acting on it (adapted from [1]).	8
2.2	Illustration of a wind turbine airfoil, showing the aerodynamic forces and relevant angles (adapted from [1]).	9
2.3	Illustration of the Actuator Disk mesh (adapted from [2]).	11
2.4	Operating principle of the baseline controller for the NREL 5MW wind turbine (from [2], based on data from [3]).	13
2.5	Illustration of the different control strategies.	14
2.6	Volume rendering of the vorticity field for the different control strategies.	15
3.1	Distribution of the normal force F_N over the AD at four time steps within one helix period T_H , comparing the four control cases.	17
3.2	Radial distribution of the normal force F_N at different azimuthal positions, evaluated at $t/T_H = 1$, for the four control cases.	18
3.3	Variation of the slope $a(\theta)$ of the normal force F_N with respect to the azimuthal position θ	19
3.4	Comparison between the approximated(....) and actual radial evolution (—) of the normal force F_N at different azimuthal positions, evaluated at $t/T_H = 1$, for the four control cases.	21
3.5	Distribution of the normal force F_N approximation over the AD at four time steps within one helix period T_H , comparing the four control cases.	22
3.6	Relative error of the normal force F_N approximation over the AD at four time steps within one helix period T_H , comparing the four control cases. The relative error is defined as $\text{error} = \frac{F_{\text{an}} - F_{\text{real}}}{F_{\text{real}}} \times 100$	23
3.7	Distribution of the tangential force F_T over the AD at four time steps within one helix period T_H , comparing the four control methods.	25

3.8	Radial distribution of the tangential force F_T at different azimuthal positions, evaluated at $t/T_H = 1$, for the four control cases.	26
3.9	Variation of the variables $a(\theta)$ and $b(\theta)$ of the tangential force F_T with respect to the azimuthal position θ	27
3.10	Comparison between the approximated(....) and actual radial evolution (—) of the tangential force F_T at different azimuthal positions, evaluated at $t/T_H = 1$, for the four control cases.	28
3.11	Distribution of the tangential force F_T approximation over the AD at four time steps within one helix period T_H , comparing the four control cases.	29
3.12	Relative error of the tangential force F_T approximation over the AD at four time steps within one helix period T_H , comparing the four control cases. The relative error is defined as $\text{error} = \frac{F_{\text{an}} - F_{\text{real}}}{F_{\text{real}}} \times 100$	30
3.13	Comparison of the new force implementation with the reference forces and the previous model version.	31
3.14	Schematic illustration of cross-flow slices taken at various streamwise positions.	33
3.15	Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, are shown for the baseline case at four downstream positions ranging from $\frac{x}{D} = 0.5$ to $\frac{x}{D} = 2$	34
3.16	Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, are shown for the static offset case at four downstream positions ranging from $\frac{x}{D} = 0.5$ to $\frac{x}{D} = 2$	35
3.17	Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, are shown for the CW helix case at four downstream positions ranging from $\frac{x}{D} = 0.5$ to $\frac{x}{D} = 2$	36
3.18	Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, are shown for the CCW helix case at four downstream positions ranging from $\frac{x}{D} = 0.5$ to $\frac{x}{D} = 2$	37
4.1	Definition of the cylindrical coordinate system	38
4.2	Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the baseline case at four downstream positions from $x/D = 0.5$ to $x/D = 2$	39
4.3	Volume rendering of the vorticity field for a baseline-controlled wind turbine.	40
4.4	Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the static offset control at four downstream positions from $x/D = 0.25$ to $x/D = 1$	41
4.5	Illustration of the induced velocities generated by a flow obstruction	42

4.6	Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the static offset control at four downstream positions from $x/D = 1.5$ to $x/D = 3.0$	43
4.7	Averaged cross-flow slices of the streamwise vorticity ω_x and the streamwise velocity u_x , taken at $T_H = 1$, are shown for the static offset control at four downstream positions from $x/D = 4.0$ to $x/D = 7.0$	44
4.8	Volume rendering of the vorticity field for a static-offset controlled wind turbine.	44
4.9	Volume rendering of the vorticity field for a CW helix-controlled wake, shown at four time steps corresponding to quarters of the helix period T_H	45
4.10	Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the CW helix case at four downstream positions from $x/D = 0.25$ to $x/D = 1$	46
4.11	Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the CW helix case at four downstream positions from $x/D = 1.5$ to $x/D = 3.0$	47
4.12	Averaged cross-flow slices of the streamwise vorticity ω_x and the streamwise velocity u_x , taken at $T_H = 1$, are shown for the CW helix case at four downstream positions from $x/D = 4.0$ to $x/D = 7.0$	48
4.13	Volume rendering of the vorticity field of the CCW helix-controlled wake, shown at four time steps corresponding to quarters of the helix period T_H	48
4.14	Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the CCW helix case at four downstream positions from $x/D = 0.25$ to $x/D = 1$	49
4.15	Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the CCW helix case at four downstream positions from $x/D = 1.5$ to $x/D = 3.0$	50
4.16	Averaged cross-flow slices of the streamwise vorticity ω_x and the streamwise velocity u_x , taken at $T_H = 1$, are shown for the CCW helix case at four downstream positions from $x/D = 4.0$ to $x/D = 7.0$	51
4.17	Illustration of the counter-rotating vortex pairs (CVP) formed in helix-controlled wakes.	51
4.18	Force distributions over the AD at four time steps within one helix period T_H for the control case with CCW helix applied to F_N and uniform F_T	52

4.19	Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, for modified and reference CCW helix case.	53
4.20	Force distributions over the AD at four time steps within one helix period T_H for the CCW helix control case without swirl	53
4.21	Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, for CCW helix case with and without swirl.	54
4.22	Velocity field of the CCW helix case without swirl	55
4.23	Performance comparison of the different control methods.	56
4.24	Performance comparison of the helix control methods with and without swirl.	56
A.1	Comparison of performance for different domain sizes.	59
B.1	Force distributions over the AD at four time steps within one helix period T_H for the control case with CW helix applied to F_N and uniform F_T	61
B.2	Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, for modified and reference CW helix control.	62
B.3	Force distributions over the AD at four time steps within one helix period T_H for the CW helix control case without swirl.	62
B.4	Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, for CW helix control with and without swirl.	63

List of Tables

2.1	Main design parameters of the NREL 5MW reference wind turbine.	12
3.1	Analytical expression of the normal force F_N for the four control cases	20
3.2	Analytical expression of the tangential force F_T for the four control cases	27
A.1	Relative error in available power downstream for different domain sizes compared to the reference domain $12D \times 12D \times 12D$	60

List of Abbreviations

Abbreviation	Full Term
IPC	Individual Pitch Control
CW	Clockwise
CCW	Counterclockwise
CVP	Counter-rotating Vortex Pair
LES	Large Eddy Simulation
F_N	Normal force
F_T	Tangential force
AL	Actuator Line
AD	Actuator Disk
ST	Static Offset Control
BL	Baseline Control
T_H	Helix Period
NUAD	Non-uniform Azimuthal Distribution

Chapter 1

Introduction

1.1 Foreword

Global warming is one of the most significant threats humanity has ever faced. Recent dramatic events such as devastating floods in Valencia, wildfires in Greece, droughts in France and record-breaking heatwaves across Europe clearly demonstrate that the consequences of climate change are both real and urgent. The last published report of the Intergovernmental Panel on Climate Change (IPCC) clearly states that global warming is mainly caused by human activities, in particular through the emission of greenhouse gases. Since 1950, global temperatures have already increased by 1.1°C , and if current policies remain unchanged, they are expected to rise between 2.2°C and 3.5°C by the end of the century [4].

To limit global warming, it is necessary to reduce greenhouse gas emissions. In Europe, the energy sector alone is responsible for 75% of these emissions [5]. In line with the European Union's objective to become climate neutral by 2050, the energy sector must adapt and move away from fossil fuels. Renewable energies appear as a key solution, as illustrated by the European Union's ambition to reach at least 65% of energy production from renewable by 2030 [5].

Solar and wind energy will account for the majority of this growth. Wind power, in particular, offers a wide range of advantages making it highly competitive. It is a mature and well-proven technology, adaptable to different scales, and operating at very low cost. According to the World Energy Outlook published by the International Energy Agency (IEA), the annual capacity additions in wind energy will need to increase from 115 GW in 2023 to 340 GW by 2030 [6].

1.2 Scope of the work and literature review

Wind farms

To take advantage of stronger and more consistent winds while avoiding noise pollution, wind turbines (WT) are often deployed in offshore locations. However, because of the increased complexity and cost of installation and maintenance, offshore turbines are often clustered in wind farms (see Figure 1.1).

Unfortunately, this clustering raises some new issues: a reduced power production for individual WT due to reduced inflow velocity, and increased fatigue loads caused by higher turbulence levels. These effects result from the fact that to generate electricity, WTs extract kinetic energy from the wind, creating a region of lower velocity and increased turbulence called the wake. These wake effects dissipate slowly downstream.

In the context of wind farms, where turbines are placed close to each other, finding strategies to speed up this wake recovery is essential to enhance the total power production and extend turbines lifetime.



Figure 1.1: Horns Rev 1 offshore wind farm property of Vattenfall - Photographer Christian Steiness.

Most WTs can be controlled by three primary actuators, which adjust:

- **Blade pitch:** rotation of the blades around their longitudinal axis.
- **Yaw angle:** orientation of the rotor about the vertical axis.
- **Generator torque:** regulation of the rotational speed.

Control strategies rely on modulating these actuators and are generally classified into two categories:

- **Static methods :** Involve slow adaptation
- **Dynamic methods :** Involve real-time adjustments

Static control methods

A first well known static control strategy is Axial Induction Control (AIC) that involves adjusting the blade pitch or the torque to modify the axial induction of upstream turbines. This reduces the power extracted by those turbines, but improves the inflow conditions for downstream ones. Although AIC has demonstrated significant effectiveness in reducing structural loads and enhancing turbine durability [7], it has shown limited success in maximizing power output across the entire wind farm [8].

Another prominent static control strategy is the Wake Steering, where the objective is to steer the wake away from downstream turbines. This is achieved through yaw control, which deliberately misaligns the WT with the wind direction, generating a transverse force that deviates the wake laterally. Although this reduces the power output of the misaligned turbine, the enhanced power generation by downstream turbines more than compensates for the initial loss [9]. More recent research has explored combined strategies integrating both AIC and Wake Steering [10]. However, the effectiveness of such combined approaches has not been fully validated to date [11].

Dynamic control methods

In addition to static methods, dynamic control strategies have been studied. The aforementioned methods also have their dynamic versions [12]. A dynamic equivalent version of AIC is the pulsed method which introduces a sinusoidal variation of the induction factor. This results in a pulsating motion in the wake that enhances wake recovery [13].

More recently, Frederik *et al.* introduced an alternative to this method, the so-called helix control [14], which will be the focus of this Master's thesis. The helix approach relies on Individual Pitch Control (IPC), meaning that the pitch of each blade can be modified independently and dynamically. Unlike pulsed method, which only induces temporal fluctuations, helix control generates spatial perturbations. While classical turbines encounter a centered, axisymmetric thrust force, IPC is here used in such way to displace the thrust's point of application in a circular path centered on the rotor.

This circular motion can be either in the same direction as the rotor rotation, known as the clockwise variant (CW), or in the opposite direction, known as the counter-clockwise variant (CCW). As a result, the wake is deformed into a helical shape. This novel method has shown very promising results in terms of power gain [15], generating strong research interest. Both numerical and experimental studies have demonstrated that CCW and CW helix do not perform equally. CCW helix seems to outperform CW helix suggesting that the helix may interact with the natural swirl of the wake [16] [17] [18].

Korb *et al.* conducted a numerical study of the wake and suggested that the better performances of the helix can be attributed to two main effects: an increased mixing of the wake as well as a radial deflection of the wake [19]. Furthermore, the wake deforms in a kidney shape similar to what was observed in yaw-deflected wakes [20]. Coquelet *et al.* suggested that this shape may be caused by the formation of a counter-rotating vortex pair (CVP) [16].

1.3 Objectives

As detailed in the previous section, the helix control has demonstrated promising results in improving wake recovery. However, a comprehensive understanding of the underlying mechanism driving these improvements is still lacking.

This Master's thesis aims to investigate the wake dynamics induced by the helix control. In particular, the observed performance gap between the CCW and CW variants is still not fully explained. The study is guided by the following key questions:

- **Question 1:** Can we confirm the formation of a CVP in helix-controlled wake? How does it contribute to the wake recovery and wake deflection?
- **Question 2:** Which specific mechanisms lead to the formation of such structures in the wake?

- **Question 3:** How can we explain the performance differences between CCW and CW?

1.4 Outline

To address those questions, Large Eddy Simulations (LES) will be conducted. This Master's thesis is structured as follow:

Chapter 2 presents the simulation framework, including a description of the flow solver, the WT modelling approach and the implementation of the IPC controller.

Chapter 3 introduces a simplified implementation of the IPC-induced forces, designed to improve numerical stability and facilitate a clearer interpretation of wake dynamics. This new implementation will be validated against the classical controller. In addition, the influence of the Reynolds number on wake behavior will be assessed to further simplify and isolate underlying mechanisms.

Chapter 4 builds on this refined framework to perform a detailed analysis of helix-controlled wakes, comparing them with other control strategies. The goal is to provide a deeper understanding of the physical mechanism that contribute to the improved performances.

Chapter 5 summarizes the key findings, discuss the limitations of the study and present some potential directions for future research.

Chapter 2

Methodology

This chapter presents the simulation framework employed throughout this study. The first section introduces the flow solver used to resolve the wind field. The second section describes the physical behavior of a WT and how its influence on the flow is modeled using an actuator disk approach. Section 3 details the WT control strategies that will be used in this Master's thesis. Finally, the numerical setup used in the simulations is presented.

2.1 Flow solver

The behavior of a wind field is described by the so-called Navier-Stokes equations. A common simplification assumes incompressible flow, i.e negligible density variations. This incompressibility assumption is valid for low Mach numbers, typically $M < 0.2$, where $M = \frac{u}{c}$ is the ratio of flow velocity to the speed of sound [21]. Under standard thermodynamic properties for dry air at sea level ($T = 288.15[K]$, $\gamma = 1.4$, $R = 287.1[\frac{J}{KgK}]$), the speed of sound is computed as:

$$c = \sqrt{\gamma RT} = 340.32[\frac{m}{s}] \quad (2.1)$$

This yields a compressibility threshold of $u = 68.06[\frac{m}{s}]$, well above typical WT operating velocities. The incompressible Navier-Stokes equations in velocity-pressure formulation reported below are therefore appropriate:

$$\nabla \cdot \mathbf{u} = 0, \quad (2.2)$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \nabla \cdot \boldsymbol{\sigma}^V + \frac{\mathbf{f}}{\rho}, \quad (2.3)$$

where $\mathbf{u}$ is the velocity vector, p the pressure, $\mathbf{f}$ the external volumetric forces vector, ρ the density and $\boldsymbol{\sigma}^V$ the viscous stress tensor.

Such system of equations is too complex to be solved analytically and requires the use of numerical methods, especially in the case of turbulent flows. Turbulence refers to the chaotic and irregular behavior of flow quantities, characterized by the formation of vortical structures called eddies. These eddies span a wide range of temporal scales and interact through the process of energy cascade: large eddies transport most of the kinetic energy, while the smallest ones dissipate it via viscous effects.

Such phenomena can be captured numerically using Direct Numerical Simulations (DNS), where all turbulent flow structures are resolved. However, this requires very refined meshes associated to high computational cost, making it unsuitable for big applications. A more computationally affordable approach is the use of Reynolds-Averaged Navier-Stokes (RANS) equations, which aim to solve only averaged flow quantities. This approach discards the details of the turbulent flow structures in favor of lower computational cost. An intermediate approach is Large Eddy Simulations (LES). LES keep computational costs manageable by resolving only the largest eddies, while the smallest ones are modelled as additional dissipative terms using subgrid-scale models.

The in-house flow solver used in this Master's thesis and developed by Duponcheel [22], relies on LES simulations. The spatial discretization is based on a fourth-order finite difference scheme introduced by Vasilyev [23], which is designed to preserve discrete kinetic energy. Time integration is performed using a fractional-step method [24]. In the first step, the momentum equation 2.3 is integrated in time to compute an intermediate velocity field. In the second step, mass conservation equation 2.2 is enforced by solving a Poisson equation for the pressure using a multigrid solver. The solver operates on a staggered Marker-and-Cell (MAC) mesh where the pressure is located at the center of the computational cells while velocity components are located on cell faces [25]. A more detailed description of the numerical method can be found in [22].

2.2 Wind turbine modelling

Physical behavior

The most widespread configuration, and the one considered in this work, is the horizontal-axis WT with three blades, as illustrated in Figure 2.1. The blades are designed using aerodynamic profiles, known as airfoils, similar to those used in aircraft wings. When air flows over an airfoil, it generates two aerodynamic forces:

- **Lift L** : acts perpendicular to flow direction
- **Drag D** : acts parallel to the flow

These forces can be decomposed in the rotor-aligned reference frame into :

- **A normal force F_N** : acts along the rotor axis
- **A tangential force F_T** : acts perpendicular to the rotor axis

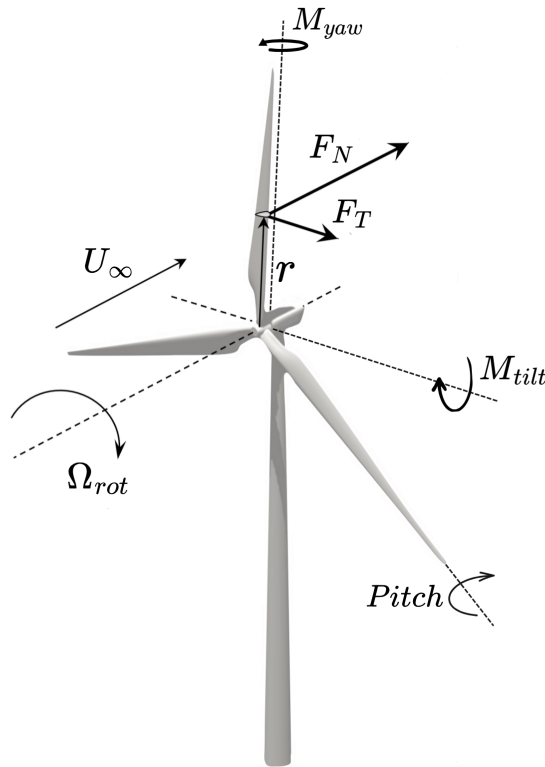


Figure 2.1: Illustration of a wind turbine showing the forces and moments acting on it (adapted from [1]).

The tangential force generates a torque that drives the rotation of the rotor, which is connected via a shaft to a generator that converts the mechanical energy into electricity. Meanwhile, the normal force produces a thrust that results in tilting and yawing moments, M_{tilt} and M_{yaw} , on the WT structure.

The flow is also subjected to reactive forces equal in magnitude and opposite in direction to those exerted on the blades. The torque imparts an angular momentum to the air in the opposite direction of the rotor rotation, inducing a swirling motion. The thrust force, on the other hand, causes a velocity deficit downstream. Both velocity deficit and swirling motion are the main characteristics of WT wakes.

The Blade Element Theory

The aerodynamic forces are computed using the Blade Element Theory [26]. It assumes that the blade can be divided in small independent elements of length Δr , such that there is no interaction between them. For each element, the local lift and drag forces are determined using 2D airfoil characteristics (see Figure 2.2): lift and drag coefficients C_L and C_D , the chord length c and the relative velocity U_{rel} experienced by the blade:

$$L = \frac{1}{2} \rho U_{rel}^2 c \Delta r C_L(\alpha) \quad (2.4)$$

$$D = \frac{1}{2} \rho U_{rel}^2 c \Delta r C_D(\alpha) \quad (2.5)$$

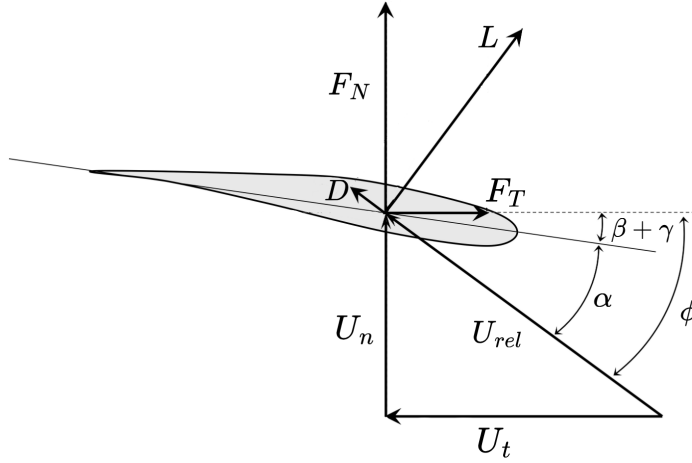


Figure 2.2: Illustration of a wind turbine airfoil, showing the aerodynamic forces and relevant angles (adapted from [1]).

U_{rel} is obtained by combining two components: U_N the difference between freestream velocity U_∞ and the normal induced velocity $U_{ind,n}$; U_T the difference between the blade tangential velocity at the given radius due to the rotation speed Ω_{rot} and the tangential induced velocity $U_{ind,t}$.

$$U_{rel} = \sqrt{U_n^2 + U_t^2} \quad (2.6)$$

$$U_n = U_\infty - U_{ind,n} \quad (2.7)$$

$$U_t = \Omega_{rot}r + U_{ind,t} \quad (2.8)$$

C_L and C_D are retrieved from tabulated airfoil data depending on the angle of attack α , which is computed from the flow angle ϕ , the twist angle γ and the pitch angle β :

$$\alpha = \phi - \beta - \gamma \quad (2.9)$$

The resulting forces can be projected onto the rotor frame to obtain F_N and F_T :

$$F_N = L \cos \phi + D \sin \phi \quad (2.10)$$

$$F_T = L \sin \phi - D \cos \phi \quad (2.11)$$

Actuator Disk

The impact of the WT on the flow is accounted for using actuator models which represent the turbine's influence over a specific region by introducing external forces $\mathbf{f}$ into the momentum balance of the Navier-Stokes Equation 2.3. Two main models exist for velocity-pressure solvers: The Actuator Line (AL) and the Actuator Disk (AD) [27].

The AL represents each blade separately as a rotating line. This allows accurate modelling of the blade rotation but requires a refined mesh to effectively capture their effects. This makes this method computationally expensive. In contrast, the AD averages the blade forces over the entire swept area, replacing the individual blade effects by a uniform distribution. This significantly reduces computational cost, making it more suitable for large-scale simulations, such as wind farms. However, because the blades are not explicitly modeled, tip vortices are not captured and are replaced by a complete vortex sheet. Moens *et al.* demonstrated that the AD is still capable of effectively handling IPC, thereby enabling the implementation of helix control [28] [29].

The AD used in this Master's thesis is shown in Figure 2.3. It is discretised into a set of elements in both radial and azimuthal directions. The AD mesh differs from

the Cartesian mesh used by the flow solver, thus they need to exchange information through a third order interpolation scheme [30].

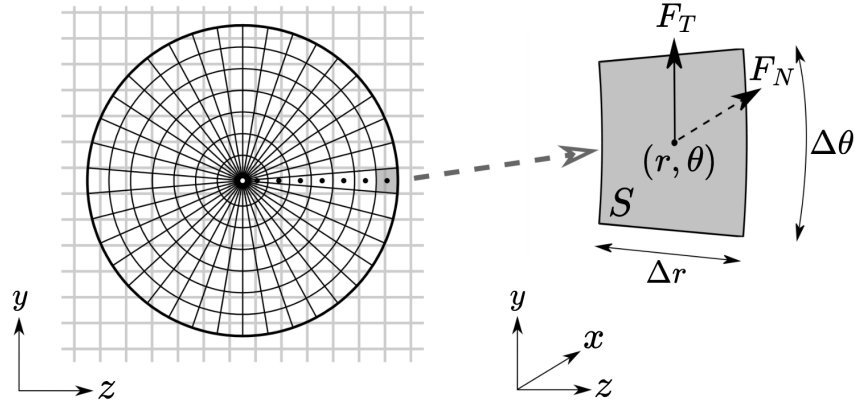


Figure 2.3: Illustration of the Actuator Disk mesh (adapted from [2]).

To ensure consistency between the AD and the flow solver, the resolution of the disk mesh is fixed such that its cell sizes remain comparable to those of the solver mesh.

Finally, as mentioned before, the forces induced by the N_b blades are computed using the blade element theory and averaged over the disk. This is done by scaling them with the ratio between the cell surface S and the corresponding ring annular surface $2\pi r\Delta r$:

$$F_{N,tot} = F_N N_b \frac{S}{2\pi r \Delta r} \quad (2.12)$$

$$F_{T,tot} = F_T N_b \frac{S}{2\pi r \Delta r} \quad (2.13)$$

To account for the missing effect of tip vortices on the blades, a tip-loss correction has been added to the AD. This correction modifies the induced velocity in order to better approximate the actual induction experienced by the blades near the tips [31].

Reference wind turbine

Simulations are performed using the NREL 5MW reference WT [3]. This academic turbine model was developed to provide a publicly available benchmark for research purposes. Its design parameters reported in Table 2.1 are representative of offshore WTs commonly deployed in wind farms.

Parameter	Value
Configuration	Upwind, 3 Blades
Rated Power	5 MW
Rotor Diameter	126 m
Hub Diameter	3 m
Hub Height	90 m
Blade Length	61.5 m

Table 2.1: Main design parameters of the NREL 5MW reference wind turbine.

2.3 Controllers

The NREL 5MW, as many modern WTs are capable of varying both its generator torque and the pitch of its blades that enables them to be controlled by three control systems:

- generator-torque controller
- Collective blade-pitch controller (CPC)
- IPC

These controllers enable us to perform and compare 4 control methods. The baseline case (BL) which consists of an Maximum Power Point Tracking (MPPT) control and serve as a reference case in the analysis, it relies on both the generator-torque controller and the CPC. The three other cases will rely on the IPC to perform the helix control, which is the main focus of our study. They will also include a static offset control (ST), which we will detail later and which helps us understand how the helix rotation affects wake dynamics.

Baseline controller

The BL case study here relies on a state-of-the-art MPPT controller. The controller's behavior depends on the turbine's operating conditions, as shown on Figure 2.4. Below the cut-in wind speed of 3 m/s (Region I), the turbine is in the start-up phase. The aerodynamic torque is not used to generate power but rather to accelerate the rotor.

Once the wind speed exceeds this threshold, the turbine starts to operate in Region II, where the objective is to maximize extracted power by maintaining an optimal tip-speed ratio.

When the wind speed surpasses the rated wind speed of 11.4 m/s (Region III), the turbine reaches its nominal power output. In this regime, the CPC is activated to adjust the blade's pitch, intentionally reducing efficiency in order to maintain power at its rated level and prevent overload issues. A more detailed description of the controller can be found in [3].

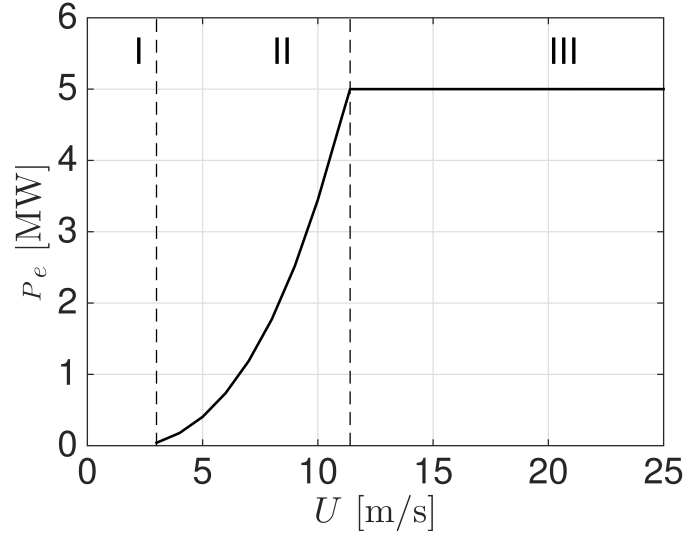


Figure 2.4: Operating principle of the baseline controller for the NREL 5MW wind turbine (from [2], based on data from [3]).

IPC-based controller

The three remaining simulation cases involve variations in the tilting and yawing moments applied to the turbine (illustrated on Figure 2.1). These variations are implemented using IPC, which dynamically changes the blade's pitch to generate the desired moments.

To convert the rotor-frame moments into individual blade pitch angle, we use of the Coleman transform [32] that maps yaw and tilt commands, β_{tilt} and β_{yaw} , to the individual pitch angles, $\beta_{1,2,3}$ based on their respective azimuthal positions $\theta_{1,2,3}$.

$$\begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} = \begin{bmatrix} \cos(\theta_1) & \sin(\theta_1) \\ \cos(\theta_2) & \sin(\theta_2) \\ \cos(\theta_3) & \sin(\theta_3) \end{bmatrix} \begin{bmatrix} \beta_{tilt} \\ \beta_{yaw} \end{bmatrix} \quad (2.14)$$

However, since the AD used in this Master's thesis does not resolve individual blades effects, the above transformation must be generalized to the n azimuthal positions of the disk cells [28]:

$$\begin{bmatrix} \beta_1 \\ \vdots \\ \beta_n \end{bmatrix} = \begin{bmatrix} \cos(\theta_1) & \sin(\theta_1) \\ \vdots & \vdots \\ \cos(\theta_n) & \sin(\theta_n) \end{bmatrix} \begin{bmatrix} \beta_{tilt} \\ \beta_{yaw} \end{bmatrix} \quad (2.15)$$

Based on this transformation, the IPC-based strategies, illustrated on Figure 2.5 and Figure 2.6, can be simply implemented by prescribing specific values for β_{tilt} and β_{yaw} depending on the case.

- **Static offset strategy :** This approach introduces a constant offset in the thrust force application point, localized in (y_T, z_T) , generating a steady yawing moment. It is defined by:

$$\beta_{tilt} = 0 \text{ and } \beta_{yaw} = A \quad (2.16)$$

- **Helix strategy:** In this case, the thrust application point follows a circular trajectory around the rotor center, generating sinusoidal variations in tilting and yawing moments at a target frequency f :

$$\beta_{tilt} = A \sin(2\pi ft) \text{ and } \beta_{yaw} = \pm A \cos(2\pi ft) \quad (2.17)$$

A positive actuation of β_{yaw} results in CCW helix, while a negative one corresponds to a CW helix.

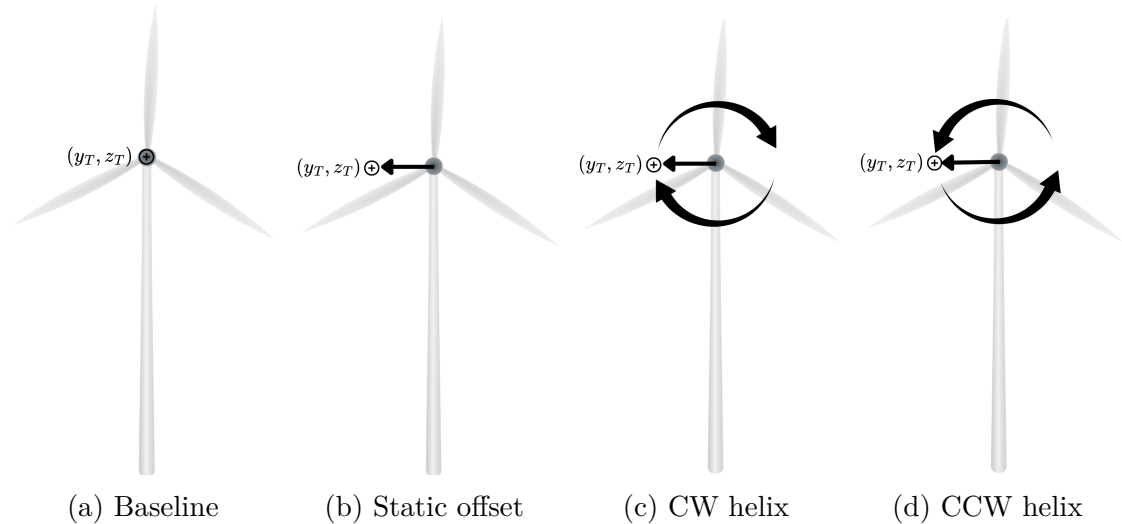


Figure 2.5: Illustration of the different control strategies.

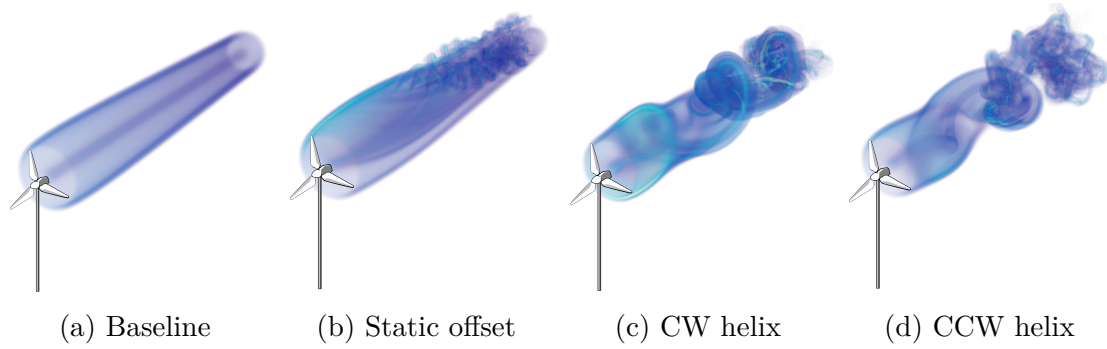


Figure 2.6: Volume rendering of the vorticity field for the different control strategies.

2.4 Numerical setup

The simulations will be performed in an under-rated regime of the WT, with an inflow velocity of $U_\infty = 9m/s$, where wake recovery strategies are particularly relevant. To simplify the wake dynamics as much as possible, the incoming flow is purely laminar.

The computational domain has dimensions $12D \times 4D \times 4D^1$ in the streamwise (x), vertical (y) and spanwise (z) directions, respectively (see Figure 2.3). As demonstrated in Appendix A, this domain size is optimal for limiting computational cost without affecting the wake. The turbine is centered at position $(3D, 2D, 2D)$. A relatively high resolution of $D/h = 64$ is used, where h is the mesh size, ensuring that the key features of the wake are well captured.

The helix control strategy is defined by a frequency corresponding to a Strouhal number of $St = \frac{fD}{U_{ref}} = 0.25$, which has been suggested in the literature to offer the best performances [14]. For our setup, it corresponds to an actuation period of $T_h = 56s$. Each simulation runs for 6 helix periods to allow the wake to fully develop.

¹ D represents the rotor diameter

Chapter 3

Numerical improvements to clarify the wake dynamics

This chapter is dedicated to improving numerical stability in order to clarify wake dynamics and facilitate further analysis. The first section focuses on modelling the aerodynamic forces induced by the WT in a way that balances simplicity and accuracy. The second section evaluates the effectiveness of this newly developed model by comparing the results with those obtained from simulations using the reference IPC forces.

3.1 Modelling of wind turbine aerodynamic forces

As mentioned earlier, the WT induces two main aerodynamic forces on the flow: the normal force F_N , responsible for the velocity deficit, and the tangential force F_T , which generates the swirl in the wake. These forces are treated separately.

We first analyse the effect of the control methods on each force to develop a suitable analytical expression. We then verify the accuracy of the implementation by comparing the modeled forces to reference ones. Afterwards, we introduce non-physical features to the force model, aiming to reduce numerical instabilities and enhance the clarity of the resulting wake structures.

3.1.1 Normal force modelling

Analytical derivation

We start our investigation with F_N , whose distribution over the AD is shown on Figure 3.1. It compares the four control cases over one complete helix period T_H .

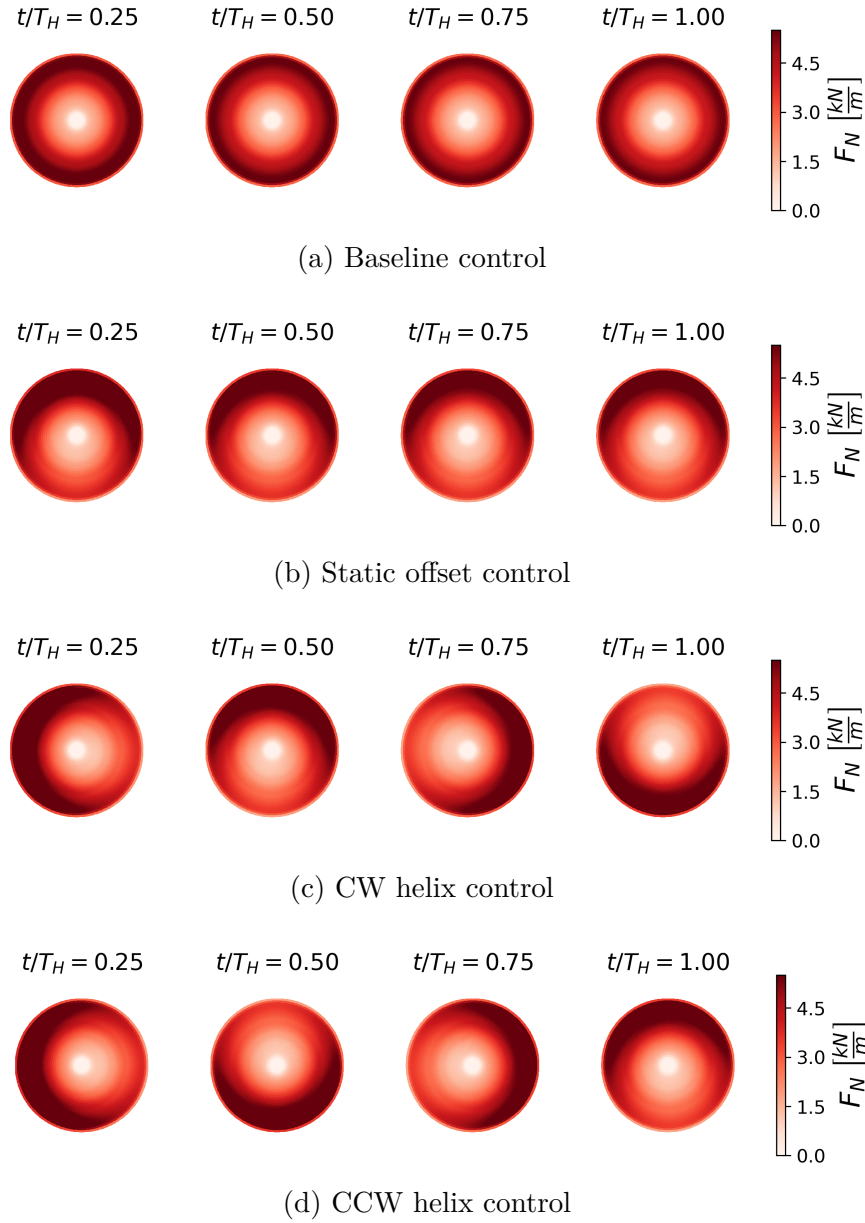


Figure 3.1: Distribution of the normal force F_N over the AD at four time steps within one helix period T_H , comparing the four control cases.

As expected, the baseline case shows a uniform azimuthal distribution of F_N that remains constant over time as there is no IPC applied. In contrast, the ST control induces a non-uniform azimuthal distribution (NUAD), creating regions of force deficit and excess. This non-uniformity is responsible for the displacement of the thrust application point. Since the offset is static, the distribution doesn't evolve

over time.

For the helix cases, a similar non-uniform force distribution is observed initially. However, it rotates over time with T_H , resulting in a rotation of the thrust application point. As expected, the direction of this rotation differs between the CW and CCW cases. Additionally, both cases begin with an initial 180° phase offset.

To reproduce the force distribution associated with helix control, we will proceed in three steps. First, we will recreate the non-uniform radial and azimuthal force distribution across the AD. Next, we will impose a rotation according to T_H , reversing the direction of rotation to differentiate between the helix control types. Finally, we will introduce a 180° initial offset for the CCW case compared to the CW case. BL and ST will be quite trivial. For the BL case, both the non-uniformity and rotation are omitted. In the ST case, the non-uniformity is retained, but the rotation over time is removed.

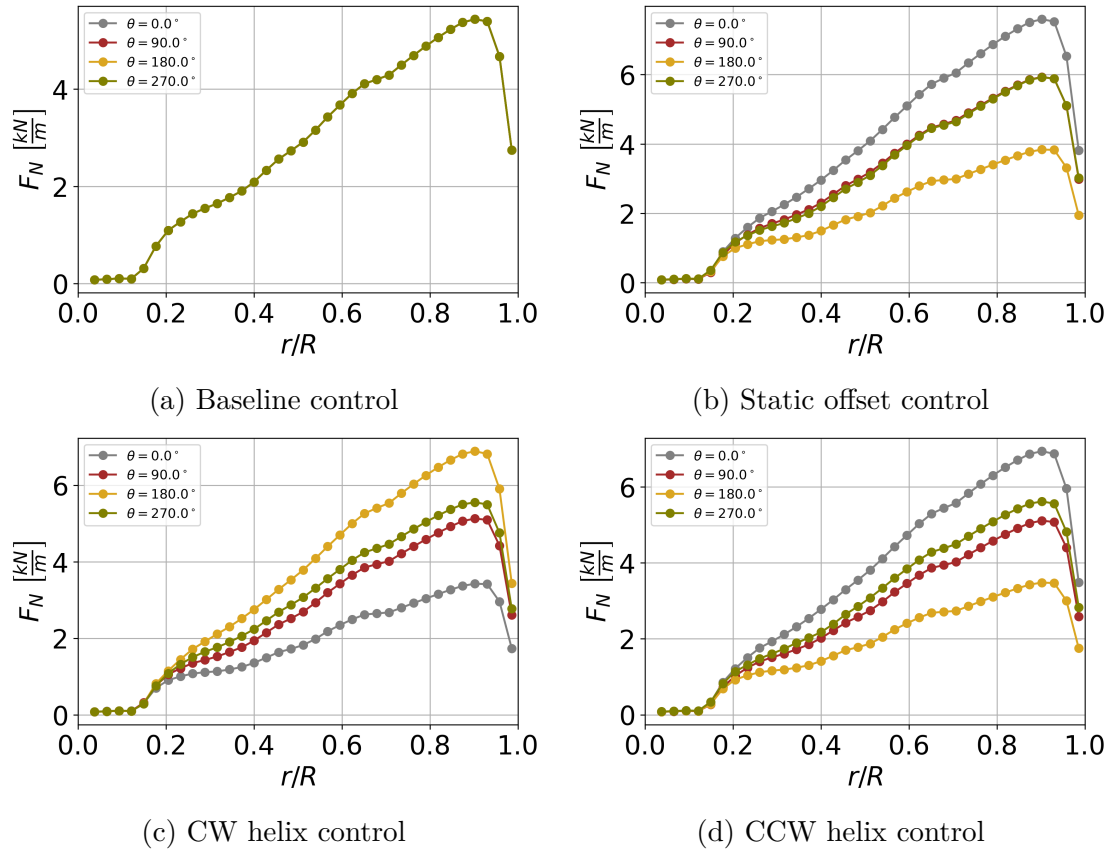


Figure 3.2: Radial distribution of the normal force F_N at different azimuthal positions, evaluated at $t/T_H = 1$, for the four control cases.

To reproduce the initial distribution, it is essential to first characterise it precisely. Figure 3.2 shows the radial evolution of F_N at different azimuthal locations. As expected, the force increases approximately linearly with radius, starting from zero at the hub and decreasing near the tip due to tip losses. In our simplified implementation, both of these effects are neglected. Therefore, a general analytical expression should be:

$$F_N(\theta, r) = a(\theta) \cdot r \quad (3.1)$$

Except in the BL case, the slope $a(\theta)$ depends on the azimuthal position. The initial NUAD is identical for both the static and helix control cases, meaning the same expression for $a(\theta)$ can be used in both. The next step is to determine this expression. Figure 3.3 shows the variation of $a(\theta)$ along the azimuthal position.

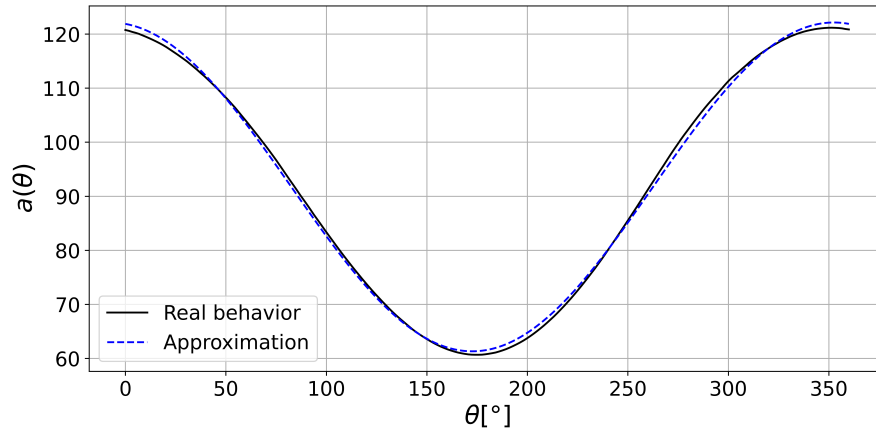


Figure 3.3: Variation of the slope $a(\theta)$ of the normal force F_N with respect to the azimuthal position θ .

The slope exhibits a sinusoidal shape and can be approximated with the general formulation:

$$a(\theta) = a_1 - a_2 \sin(\theta) \quad (3.2)$$

where a_1 and a_2 are some adjustable constants used to match the evolution of the slope. In the BL case, since the distribution is uniform, we have $a_2 = 0$. Figure 3.3 finally shows the analytical approximation with the chosen parameter (in blue dotted line) that closely matches the real behavior.

The next step is to account for the rotation of the helix cases by introducing a time-dependent phase shift and initial offset:

$$a(\theta) = a_1 - a_2 \sin(\theta + \phi(t)) \quad (3.3)$$

with

$$\phi(t) = \begin{cases} \frac{t}{T_H} \cdot 2\pi & \text{if } CW, \\ -\frac{t}{T_H} \cdot 2\pi + \pi & \text{if } CCW. \end{cases} \quad (3.4)$$

Table 3.1 summarises the expressions used to model F_N distribution for each control cases.

Case	$F_N(\theta, r, t) =$
Baseline	$a_1 \cdot r$
Static Offset	$(a_1 - a_2 \sin \theta) \cdot r$
Helix CW	$\left(a_1 - a_2 \sin \left(\theta + \frac{2\pi t}{T_H}\right)\right) \cdot r$
Helix CCW	$\left(a_1 - a_2 \sin \left(\theta - \frac{2\pi t}{T_H} + \pi\right)\right) \cdot r$

Table 3.1: Analytical expression of the normal force F_N for the four control cases

Verification

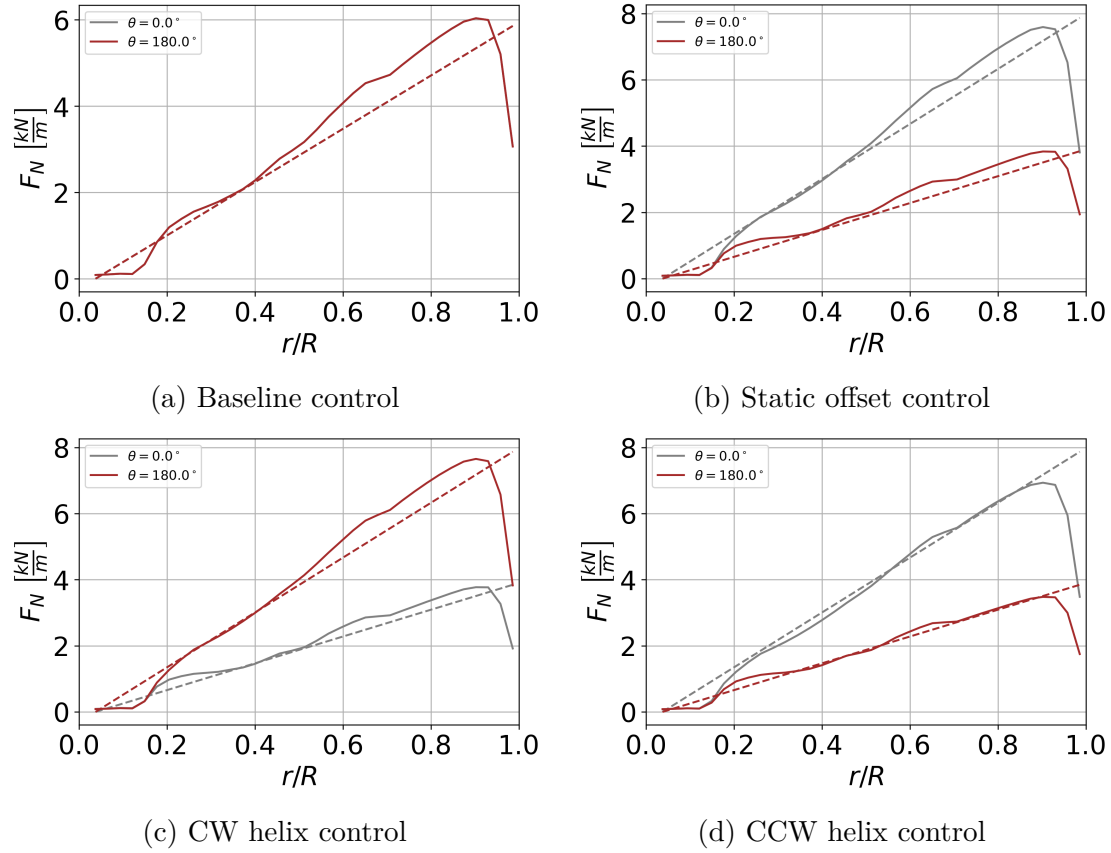
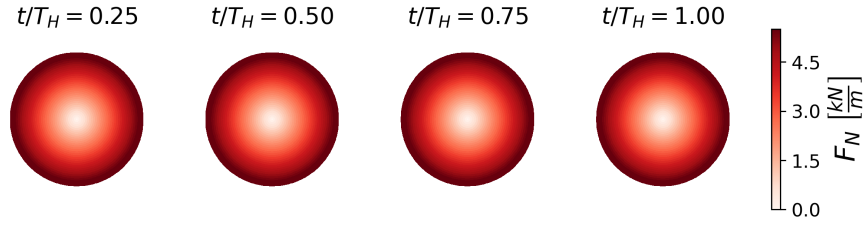


Figure 3.4: Comparison between the approximated(.....) and actual radial evolution (—) of the normal force F_N at different azimuthal positions, evaluated at $t/T_H = 1$, for the four control cases.

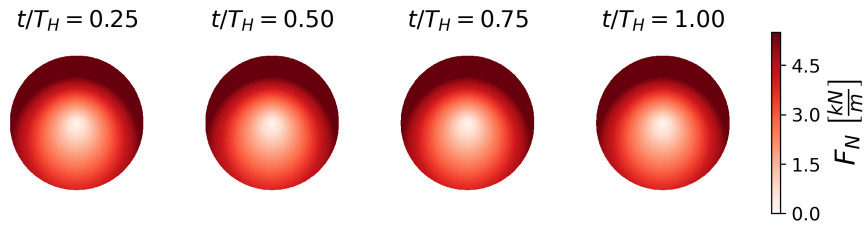
Now that the implementation of F_N has been developed, it is necessary to verify its accuracy by comparing it to the reference IPC forces. Figure 3.4 presents this comparison, showing the reference IPC forces and the analytical approximation. The implementation effectively reproduces the initial F_N distribution and its radial evolution, except near the hub and tip regions, where simplifications were made. Additionally, the slope of the analytical approximation closely follows the real one across all control cases.

To further assess the global behavior, Figure 3.5 displays the full AD representation of F_N approximation. As expected, the BL case exhibits a uniform and time-invariant force distribution. The static offset case shows the NUAD that remains stationary, which is accurately captured by the model. For the helix-controlled

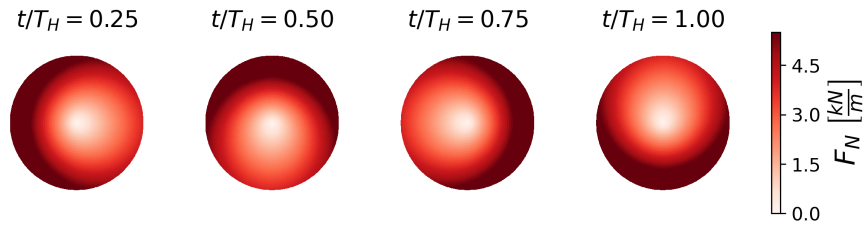
cases, the NUAD rotates over time, and this rotation is correctly reproduced through the time-dependent phase shift of our formulation.



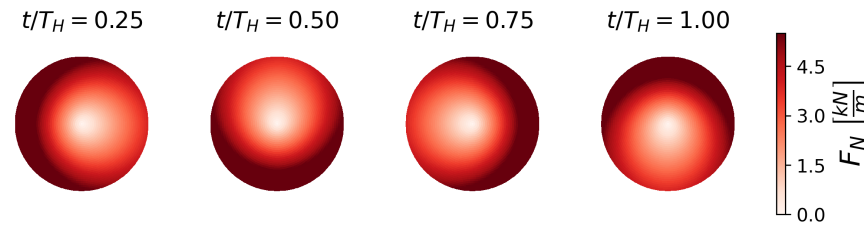
(a) Baseline control



(b) Static offset control



(c) CW helix control



(d) CCW helix control

Figure 3.5: Distribution of the normal force F_N approximation over the AD at four time steps within one helix period T_H , comparing the four control cases.

To fully validate the implementation, Figure 3.6 presents the relative error between the analytical approximation and the reference IPC forces.

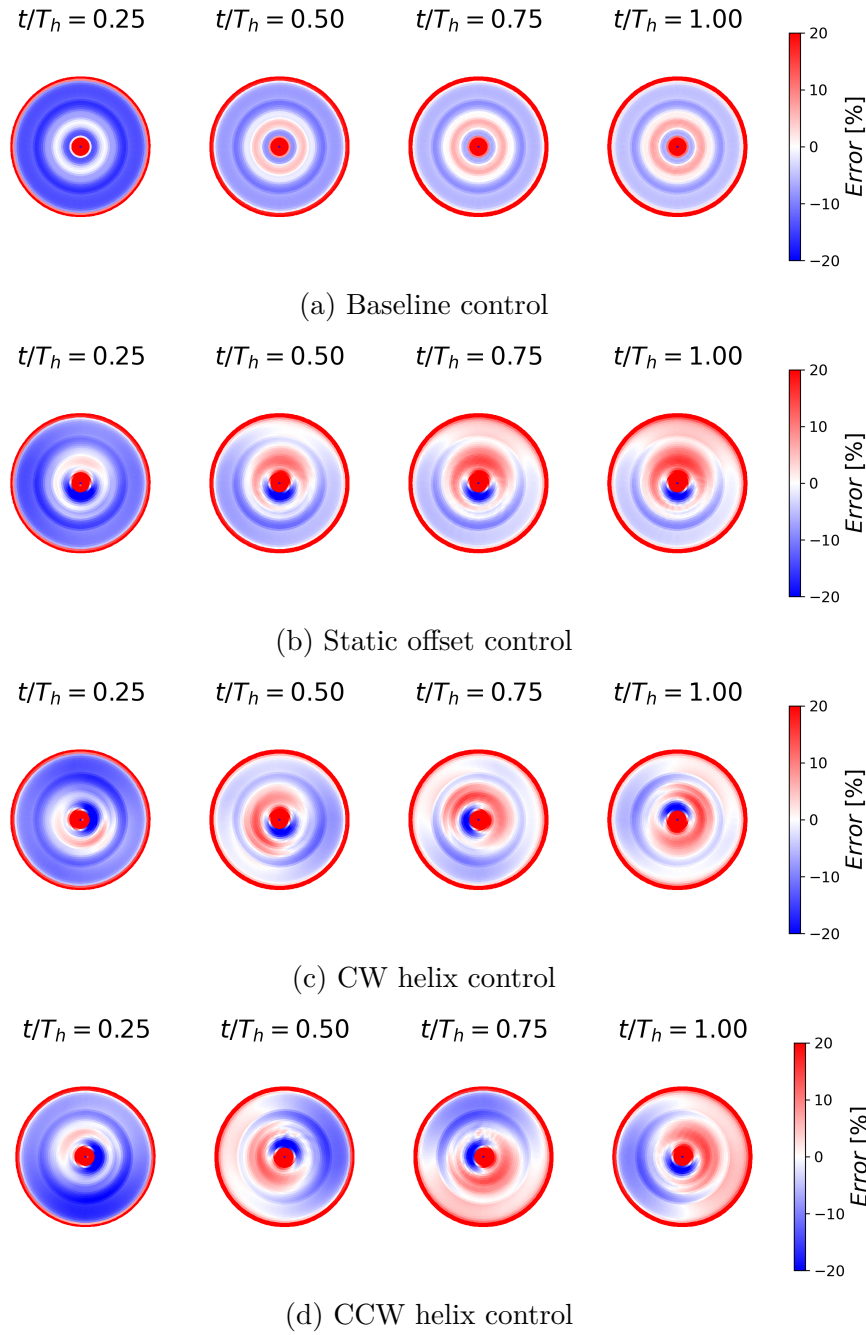


Figure 3.6: Relative error of the normal force F_N approximation over the AD at four time steps within one helix period T_H , comparing the four control cases. The relative error is defined as $\text{error} = \frac{F_{\text{an}} - F_{\text{real}}}{F_{\text{real}}} \times 100$.

Notably, the error is significant at the disk's edge and center, due to the omission

of tip-loss and hub corrections. Some discrepancies remain inside the AD due to the inherent limitations of the linear approximation. Addressing this issue would require developing a more detailed analytical model, which deviates from the initial objective of simplifying the force calculations. Outside the regions near the hub and blade tip, the relative error remains minimal, staying below 10%. This highlights the effectiveness of our analytical approximation across most of the AD.

3.1.2 Tangential force modelling

Analytical derivation

We now turn to the implementation of F_T . Figure 3.7 displays its distribution on the AD for the four control cases.

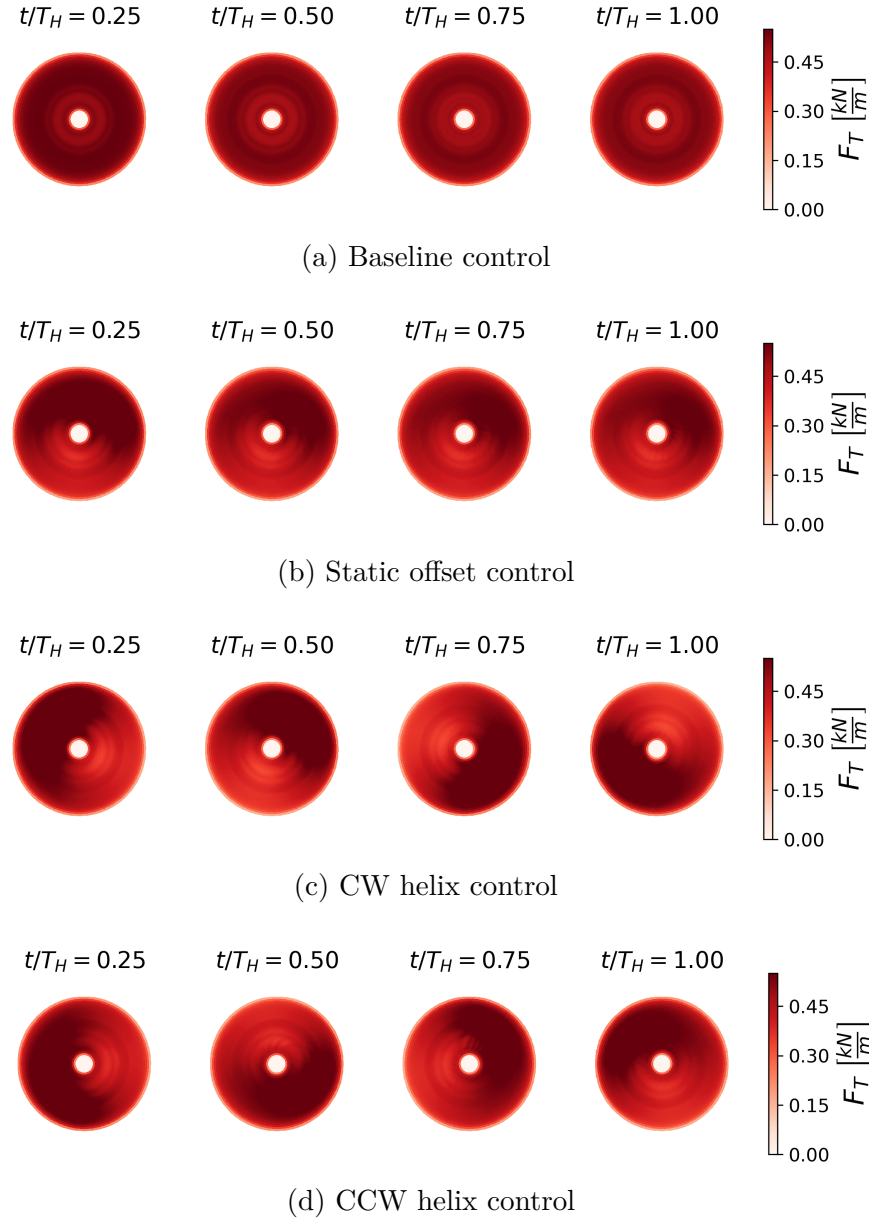


Figure 3.7: Distribution of the tangential force F_T over the AD at four time steps within one helix period T_H , comparing the four control methods.

As expected, F_T exhibits the same behavior as F_N . In the baseline case, the distribution is uniform azimuthally and time independent. In contrast, the static offset and helix cases show a NUAD, stationary for the static offset case and rotating over time for the helix cases. Given these similarities, the implementation of F_T follows the same procedure as for F_N .

Things get different when we start looking at the initial distribution shown on Figure 3.8. In this case, the analytical approximation becomes slightly more complex. F_T can be divided into two distinct regions: a linear evolution before $r/R = 0.25$, and a constant value thereafter. As before, a tip loss correction will not be considered. Therefore, F_T can be approximated as follows:

$$F_T(\theta, r) = \begin{cases} a(\theta) \cdot r & \text{if } r/R < 0.25 \\ b(\theta) & \text{if } r/R \geq 0.25 \end{cases} \quad (3.5)$$

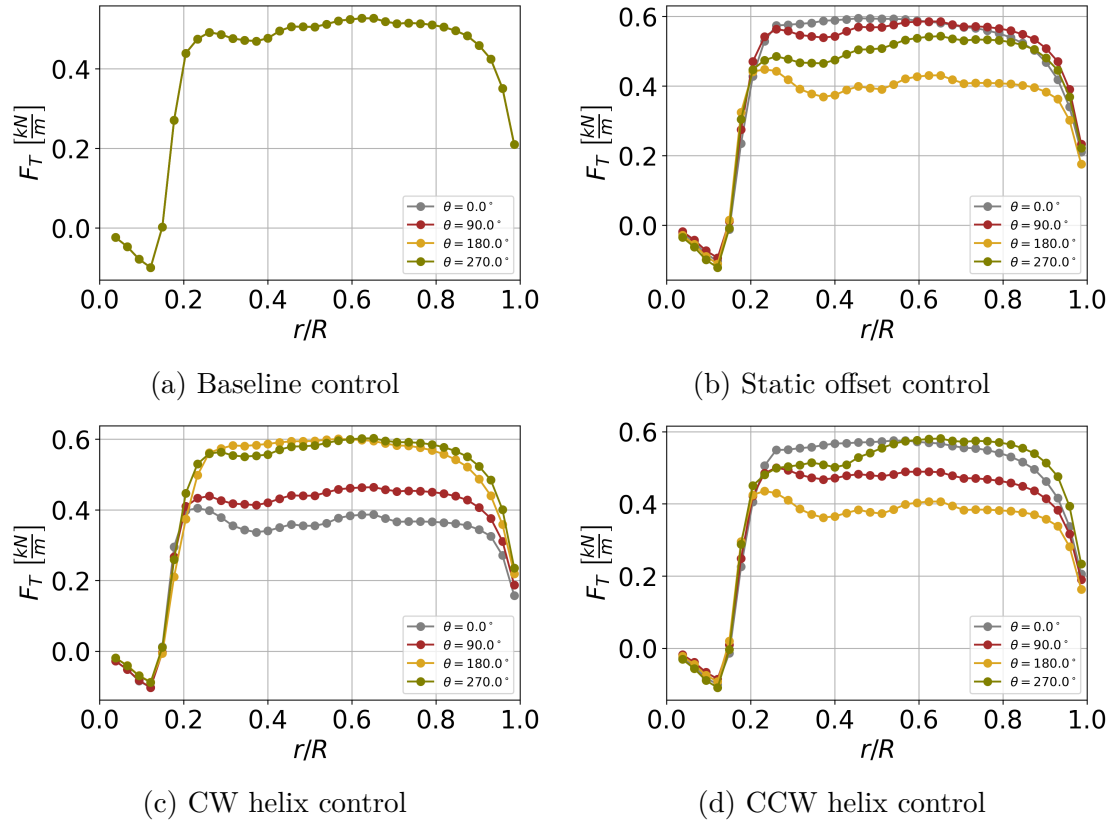


Figure 3.8: Radial distribution of the tangential force F_T at different azimuthal positions, evaluated at $t/T_H = 1$, for the four control cases.

In the BL case, both a and b remain constant. However, for the other control cases, they vary with the azimuthal position. Figure 3.9 illustrates this evolution to support the development of a suitable approximation.

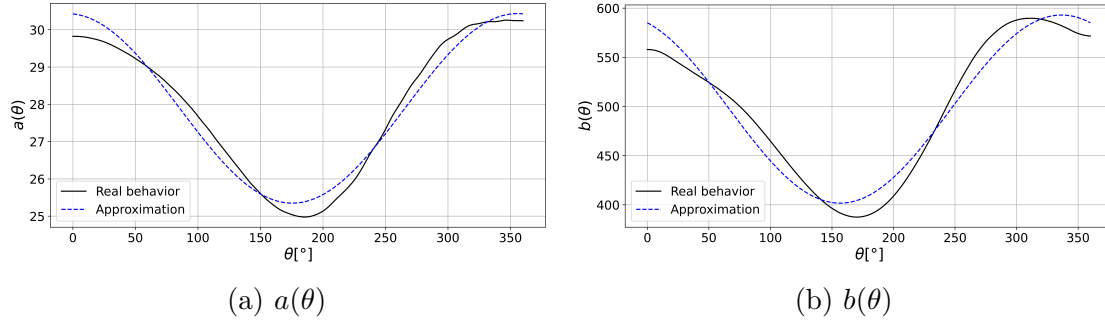


Figure 3.9: Variation of the variables $a(\theta)$ and $b(\theta)$ of the tangential force F_T with respect to the azimuthal position θ .

As observed, both parameters can be reasonably approximated using simple sinusoidal functions:

$$\begin{cases} a(\theta) = a_1 - a_2 \sin(\theta + \phi(t)) \\ b(\theta) = b_1 - b_2 \sin(\theta + \phi(t)) \end{cases}$$

The parameters a_1 , a_2 , b_1 , and b_2 are tuned to match the actual behavior as shown in Figure 3.9 (in blue dotted line). $\phi(t)$ corresponds to the same phase shift used for F_N , as defined in Equation 3.4. In the BL case, we set $a_2 = 0$ and $b_2 = 0$, reflecting the uniform force distribution. For the static offset case, $\phi(t) = 0$, resulting in a time-invariant distribution. Table 3.2 summarizes the implementation of F_T approximation.

Case	$F_T(\theta, r, t) = a(\theta) \cdot r$ if $r/R < 0.25$	$F_T(\theta, r, t) = b(\theta)$ if $r/R \geq 0.25$
Baseline	$a(\theta) = a_1$	$b(\theta) = b_1$
Static Offset	$a(\theta) = a_1 - a_2 \sin \theta$	$b(\theta) = b_1 - b_2 \sin(\theta)$
Helix CW	$a(\theta) = a_1 - a_2 \sin\left(\theta + \frac{2\pi t}{T_H}\right)$	$b(\theta) = b_1 - b_2 \sin\left(\theta + \frac{2\pi t}{T_H}\right)$
Helix CCW	$a(\theta) = a_1 - a_2 \sin\left(\theta - \frac{2\pi t}{T_H} + \pi\right)$	$b(\theta) = b_1 - b_2 \sin\left(\theta - \frac{2\pi t}{T_H} + \pi\right)$

Table 3.2: Analytical expression of the tangential force F_T for the four control cases

Verification

As with F_N , it is important to verify the accuracy of the F_T approximation. Figure 3.10 compares the analytical and reference F_T in terms of their radial evolution. The implementation successfully reproduces the radial evolution and appears to capture the azimuthal variation with good accuracy.

This is further confirmed in Figure 3.11, which shows the full AD distribution. The overall pattern is well captured by the approximation. As expected, the BL case exhibits a uniform distribution. In contrast, the other control cases display a NUAD: it remains stationary in the static offset case, while in the helix cases it rotates over time in the prescribed direction.

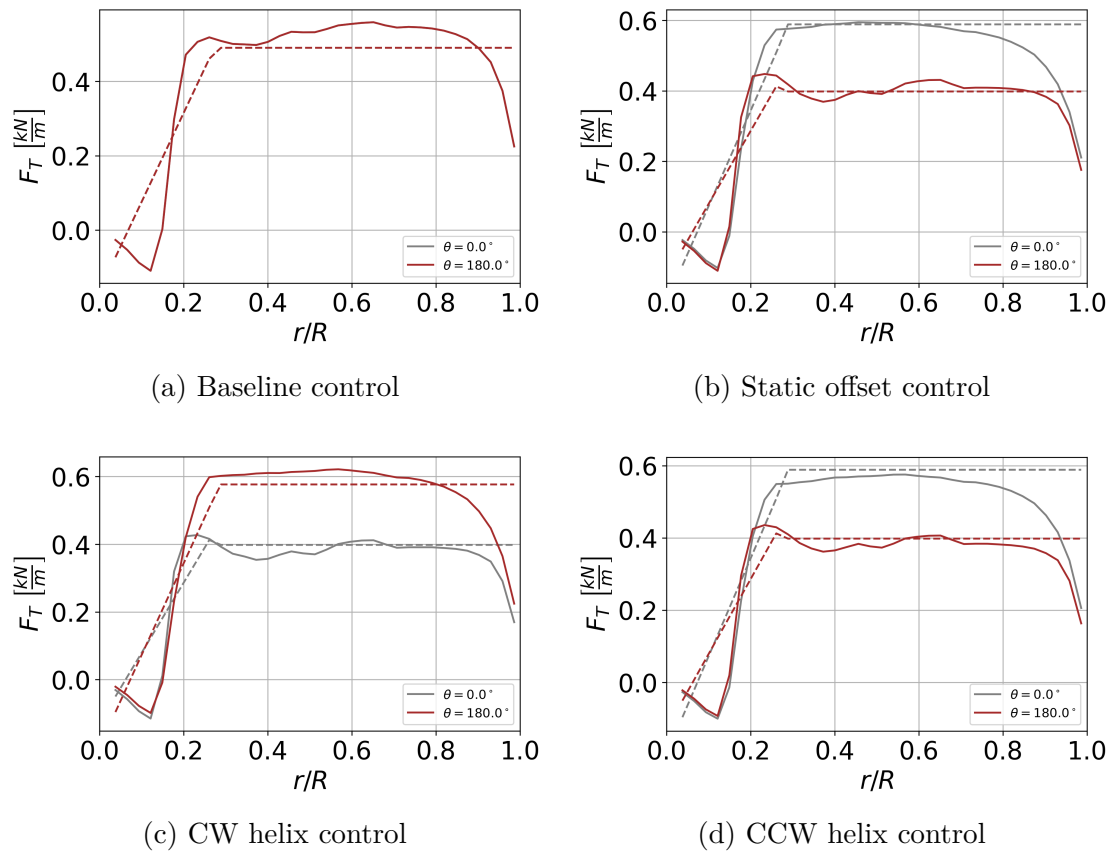


Figure 3.10: Comparison between the approximated(---) and actual radial evolution (—) of the tangential force F_T at different azimuthal positions, evaluated at $t/T_H = 1$, for the four control cases.

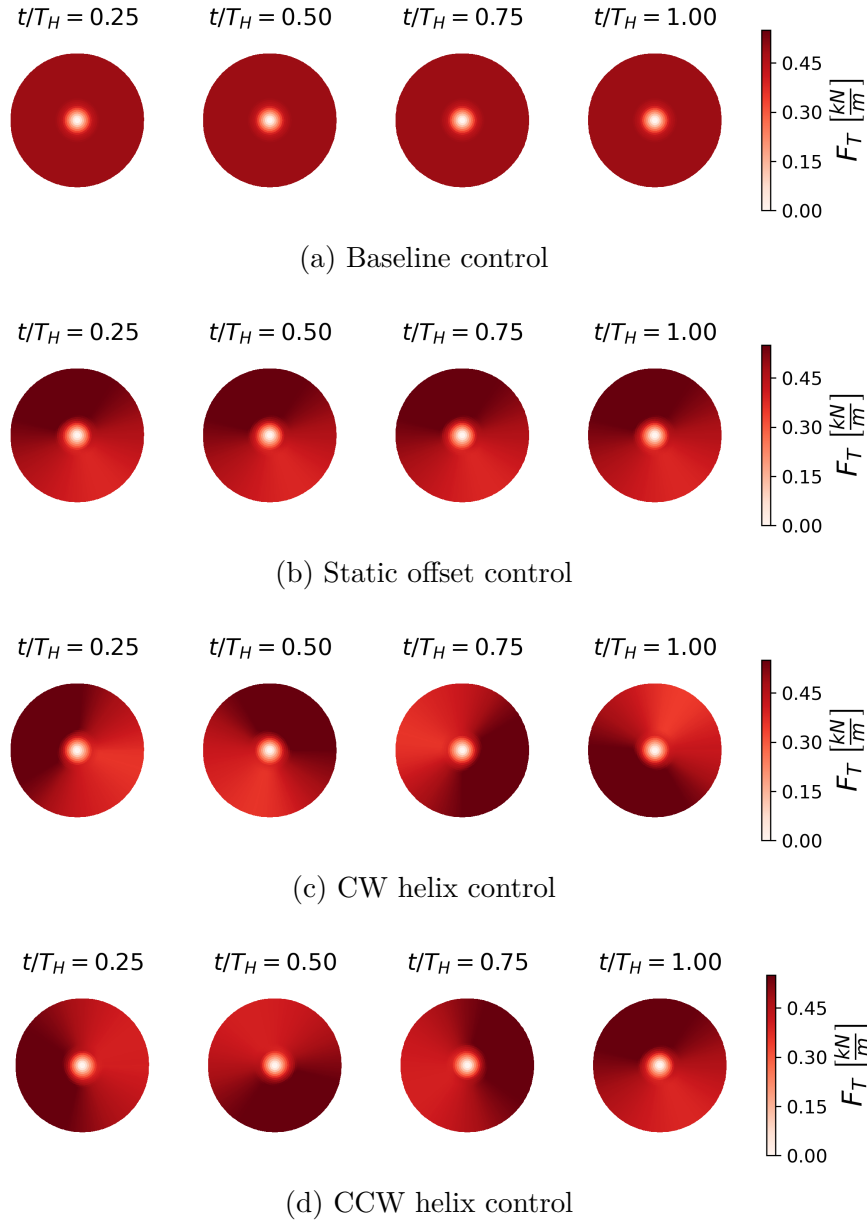


Figure 3.11: Distribution of the tangential force F_T approximation over the AD at four time steps within one helix period T_H , comparing the four control cases.

To conclude, Figure 3.12 presents the relative error between the approximated and reference F_T . As before, the error remains relatively low outside the hub and tip regions, confirming the overall effectiveness of the implementation. However, it is worth noting that the ST case exhibits a more significant error within the actuator disk. This is due to an additional phase offset present in F_T , which does

not appear in F_N and was deliberately omitted for simplicity. Nonetheless, this small difference is not expected to have a significant impact on the resulting wake dynamics.

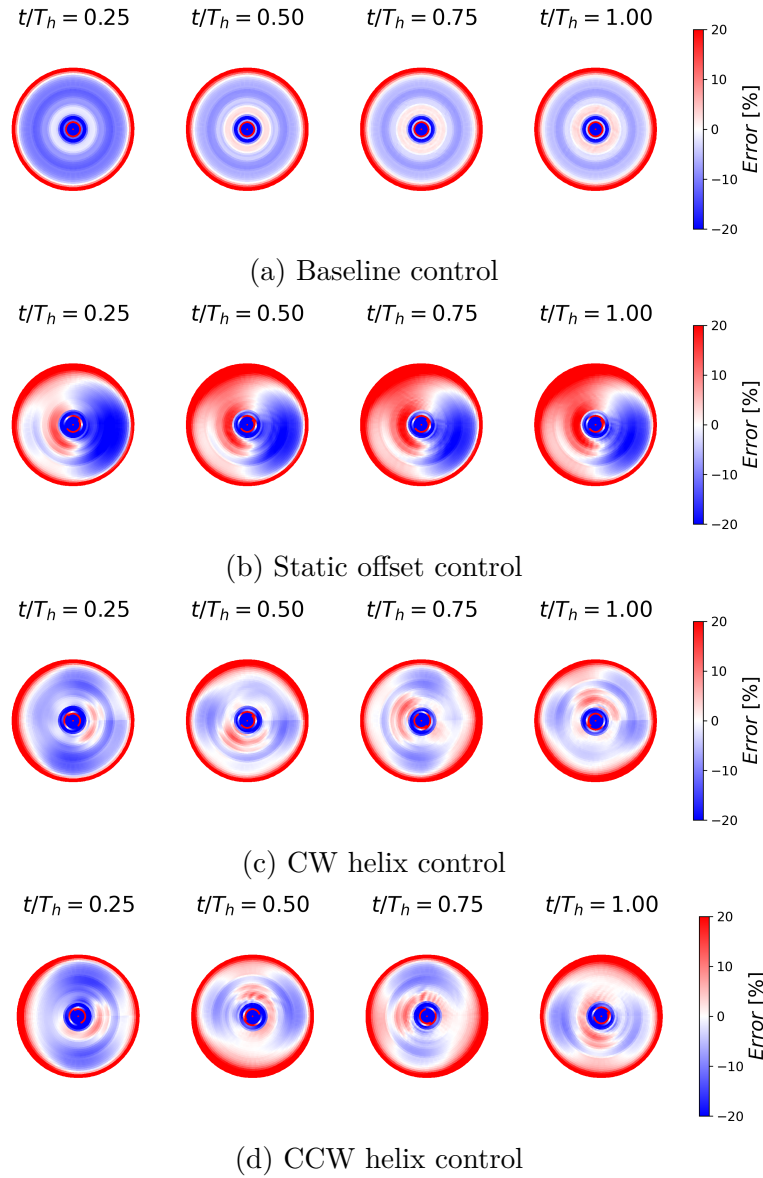


Figure 3.12: Relative error of the tangential force F_T approximation over the AD at four time steps within one helix period T_H , comparing the four control cases. The relative error is defined as $\text{error} = \frac{F_{\text{an}} - F_{\text{real}}}{F_{\text{real}}} \times 100$.

3.1.3 Additional features for enhanced numerical stability

Finally, some numerical instabilities could be caused by the strong gradient near the tip of the disk [33], where the force reaches its maximum before dropping to zero outside. To avoid this, we decided to implement a Gaussian regularization function to smooth the force distribution near the extremities. For F_N , this translates to:

$$F_N(\theta, r) = \begin{cases} a(\theta) \cdot r & \text{if } \frac{r}{R} < 0.8 \\ a(\theta) \cdot r \cdot \exp\left(-\frac{(r - 0.8R)^2}{\sigma^2}\right) & \text{if } \frac{r}{R} \geq 0.8 \end{cases} \quad (3.6)$$

The same approach is applied to F_T :

$$F_T(\theta, r) = \begin{cases} b(\theta) \cdot (1 - \exp\left(-\frac{r^2}{\sigma^2}\right)) & \text{if } \frac{r}{R} < 0.3 \\ b(\theta) & \text{if } 0.3 \leq \frac{r}{R} < 0.8 \\ b(\theta) \cdot \exp\left(-\frac{(r - 0.8R)^2}{\sigma^2}\right) & \text{if } \frac{r}{R} \geq 0.8 \end{cases} \quad (3.7)$$

Here, σ is the parameter controlling the shape of the Gaussian function.

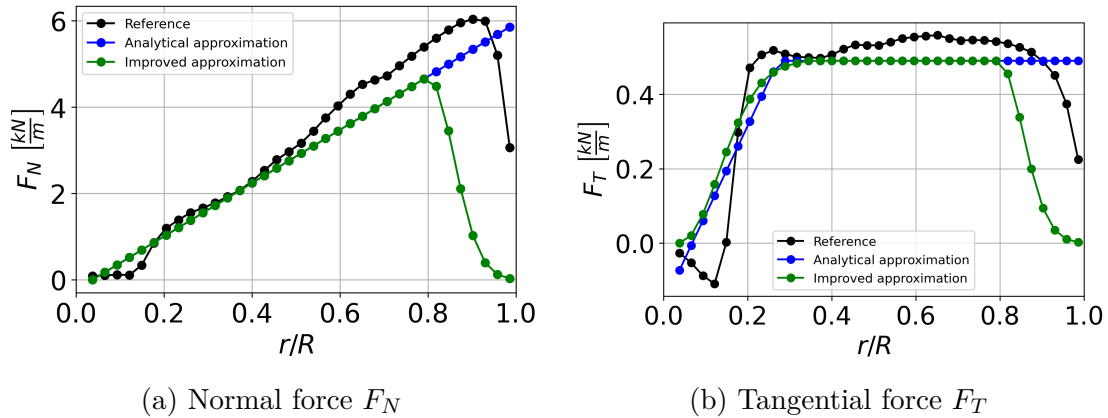


Figure 3.13: Comparison of the new force implementation with the reference forces and the previous model version.

Figure 3.13 illustrates this new version of the model, compared to the previous one and to the reference forces. We observe that the objective of smoothly bringing F_N and F_T to zero at the extremities is successfully achieved.

However, the introduction of these new features leads to a deviation from the actual force distribution in certain regions. While this should have little impact

on the wake dynamics since the overall force patterns are preserved (see Section 3.2). It becomes more critical when evaluating performance, as the integrated force values are significantly altered. As a consequence, all further performance assessments of the control methods should be evaluated relative to each other, rather than interpreted as absolute values.

3.2 Effect of the force approximation model on wake dynamics

In this section, we begin the wake analysis to validate that the main wake features are accurately reproduced by our approximate force model. At the same time, we aim to verify whether the key aspects of wake dynamics recently highlighted by Coquelet *et al.* [16] are also present in our results. The objective here is not to provide a detailed physical interpretation, that will be the focus of the next chapter, but to carry out a first-step validation and establish an initial understanding of the flow behavior.

Simulations using our approximate force model were performed at two Reynolds numbers: $Re = 10^8$ and $Re = 10^4$. The Reynolds number, defined as $Re = \frac{uD}{\nu}$, quantifies the ratio of inertial to viscous forces. A lower Reynolds number corresponds to a laminar flow regime with increased viscous effects and reduced turbulence, which simplifies the wake structure and facilitates the isolation of fundamental wake dynamics.

To isolate the vortical structures of the wake, we use the vorticity vector defined as:

$$\boldsymbol{\omega} = \nabla \times \mathbf{u} \quad (3.8)$$

To capture the evolution of these structures as the wake expands downstream, we examine 2D slices of the wake at different streamwise positions, as illustrated in Figure 3.14.¹

¹Note that Figure 3.14 is not to scale and serves only as a schematic representation.

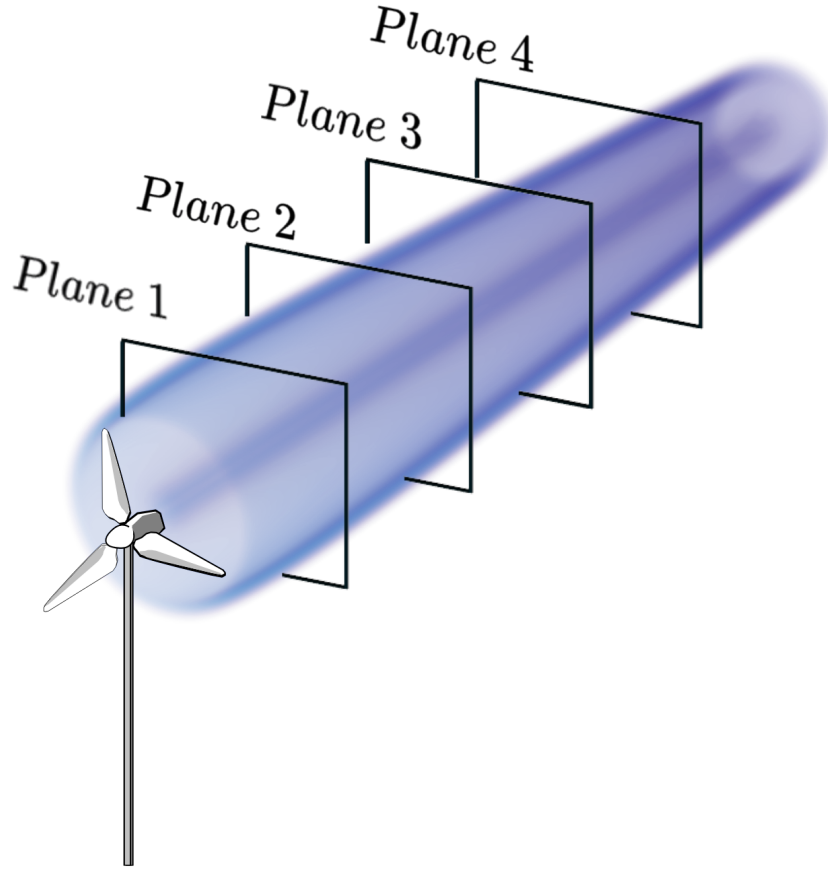


Figure 3.14: Schematic illustration of cross-flow slices taken at various streamwise positions.

3.2.1 Baseline control

We start our analysis with the BL case. Figure 3.15 presents cross-flow slices of the streamwise vorticity component at four downstream positions, illustrating the evolution of the wake structure. The comparison includes three simulations: one using the reference forces and two others using the approximate force model at different Reynolds numbers ($Re = 10^8$ and $Re = 10^4$). Results from the approximate force model are further time-averaged to reduce any remaining numerical errors.

We first observe that the reference simulation exhibits significant numerical errors, which are entirely removed with the new force model, thus validating its primary objective. Secondly, the Re appears to have little influence in this case, as the wake structure remains relatively simple.

Concerning the wake vortical structures, we observe two distinct regions of high vorticity, commonly referred to as the tip and hub vortices. Tip vortices are generated near the blade tips due to the strong spanwise pressure gradient, which induces a rolling-up of the shear layer between the rotating blade tip and the surrounding flow.

In our case, since we use an AD model, these tip vortices are not explicitly resolved but are instead represented as a continuous vortex sheet near the disk edge. Similarly, the presence of the hub in the WT induces a central region of negative vorticity, known as hub vorticity. In this BL case, the overall structure of these vortical regions remains relatively stable and does not show significant downstream evolution.

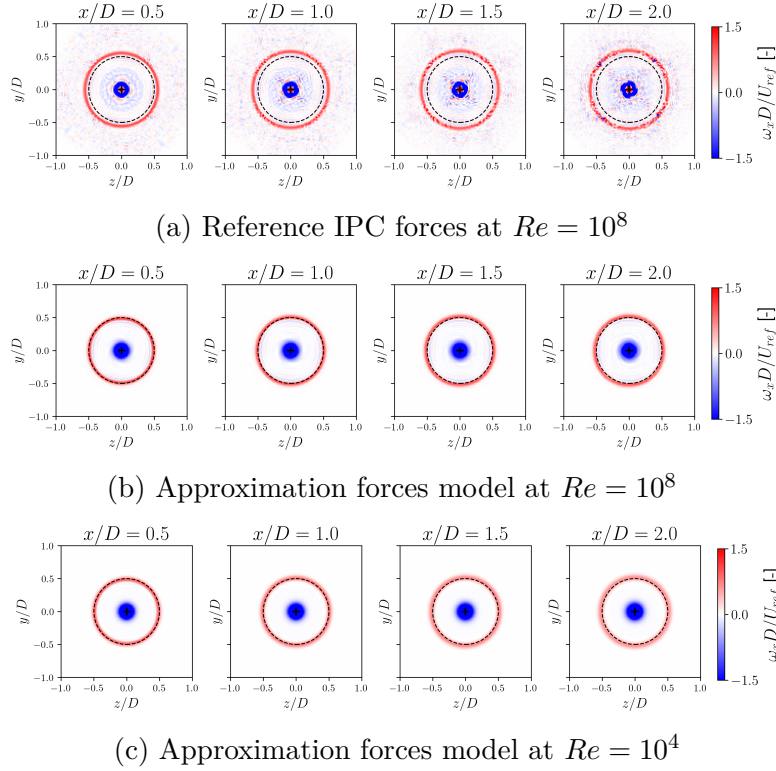


Figure 3.15: Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, are shown for the baseline case at four downstream positions ranging from $\frac{x}{D} = 0.5$ to $\frac{x}{D} = 2$.

3.2.2 Static offset control

The ST case once again confirms the benefits of the approximate force model, which significantly improves the quality of the results, as illustrated in Figure 3.16. The hub and tip vortices are still present. However, in contrast to the previous case, additional vorticity regions appear inside the wake. Indeed, two lobes of opposite vorticity form, as previously reported by Coquelet *et al.* [16], resulting from the NUAD of the forces.

As the wake evolves downstream, the hub vortex begins to rotate in the CCW direction, while the behavior of the vortex sheet varies with the Re . At high Re , the vortex sheet destabilizes near the positive lobe as early as $x/D = 0.5$, leading to the breakdown of both lobes and the hub vortex. At low Re , the vortex sheet remains stable but exhibits the emergence of a negative vortex at $x/D = 1.5$, which then forms a co-rotating vortex pair with the hub vortex at $x/D = 2.0$.

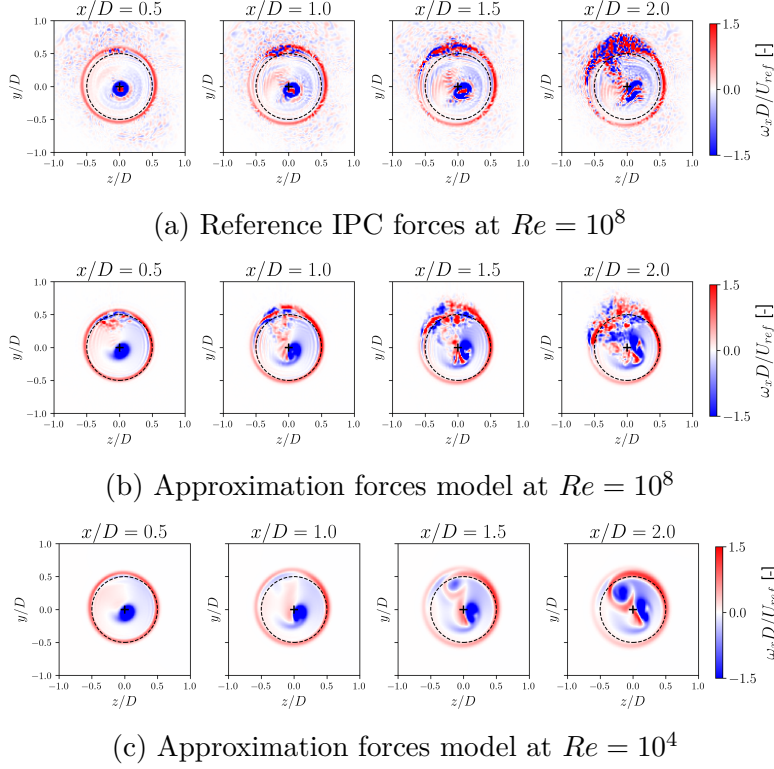


Figure 3.16: Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, are shown for the static offset case at four downstream positions ranging from $\frac{x}{D} = 0.5$ to $\frac{x}{D} = 2$.

3.2.3 CW helix control

When we turn our attention to the helix control method, the use of the approximate model becomes not just a clarification tool but a necessity to clearly observe the underlying mechanisms, as illustrated in Figure 3.17. In this configuration, the Re no longer appears to significantly influence the mechanism, unlike in previous cases.

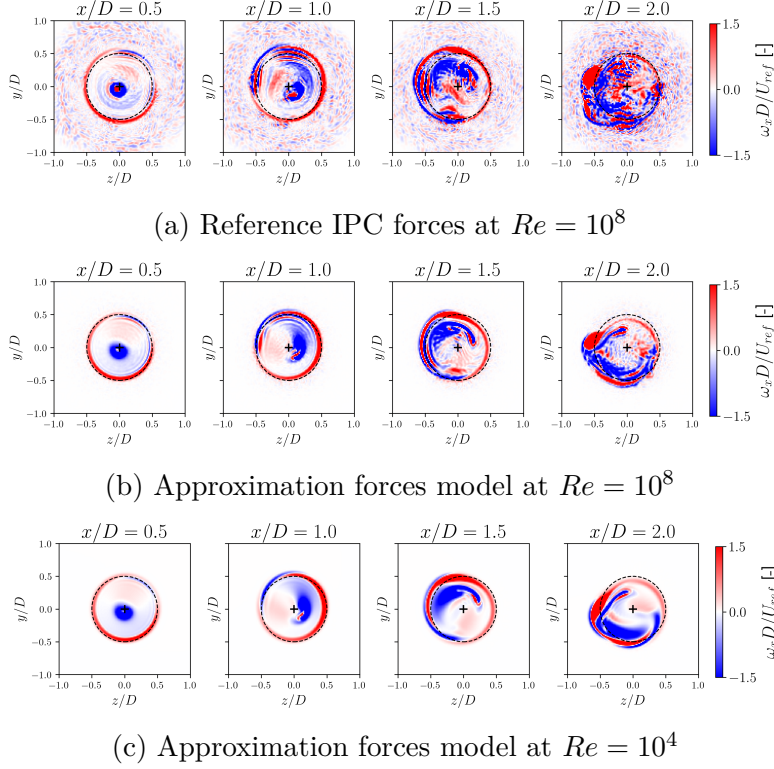


Figure 3.17: Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, are shown for the CW helix case at four downstream positions ranging from $\frac{x}{D} = 0.5$ to $\frac{x}{D} = 2$.

Compared to the BL and ST cases, the rotation of the thrust application point generates a helical wake structure (see Figure 2.6). This indicates that the flow structures rotate as they are convected downstream. Specifically, at $x/D = 0.5$, we observe the same main features as in the ST case, tip and hub vortices as well as two lobes of opposite vorticity, but these lobes now follow the wake rotation.

In this case, the hub vortex is stretched azimuthally and merges with the negative lobe at $x/D = 1.0$, before being further assimilated into the vortex sheet at $x/D = 1.5$. Coquelet *et al.* reported a strengthening of the positive lobe, which

is not observed here. Instead, we begin to see the early formation of a positive vortex inside the vortex sheet at $x/D = 2.0$, a feature also recently reported by Gutknecht *et al.* [34].

3.2.4 CCW helix control

The CCW helix control, illustrated in Figure 3.18, induces a significantly different wake dynamics compared to the CW case. The initial tip vortex, hub vortex, and lobe vorticity remain similar to those observed previously. As expected, the wake and structures rotate in the opposite direction than CW helix. However, in this case, the hub vortex remains within the wake, rotating and being pushed outward from the center, replacing the positive vorticity lobe. Meanwhile, the negative vorticity lobe strengthens near the tip at $x/D = 1.0$, eventually forming again a system of co-rotating vortex pairs at $x/D = 2.0$, similar to the observations reported by Coquelet *et al.*

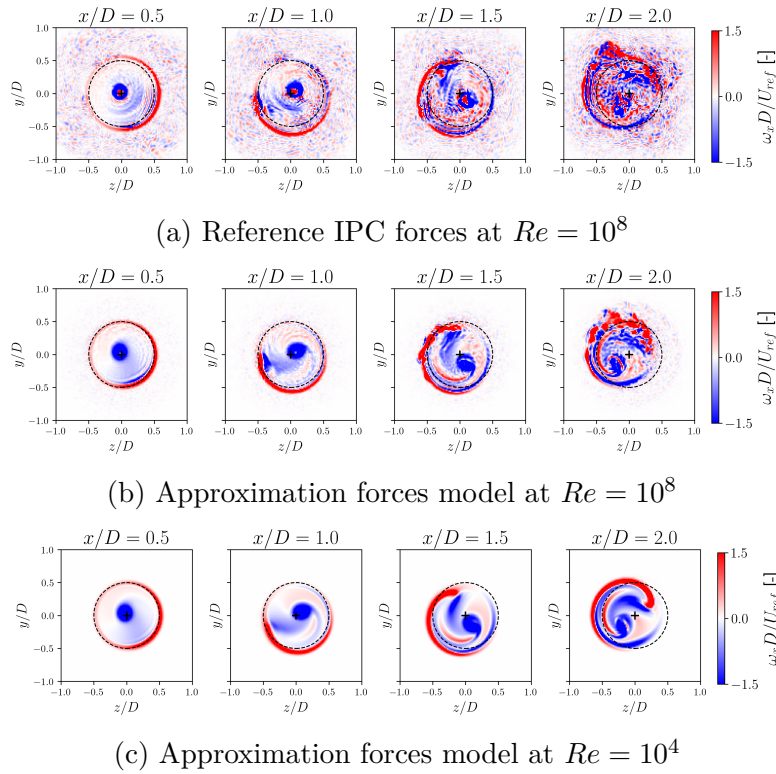


Figure 3.18: Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, are shown for the CCW helix case at four downstream positions ranging from $\frac{x}{D} = 0.5$ to $\frac{x}{D} = 2$.

Chapter 4

Investigation of wake dynamics

This chapter presents a detailed analysis of the wake. For each control method, we first examine how the force distribution influences the initial wake and leads to the structures observed in Section 3.2. We then investigate the downstream evolution of these structures and assess how they might explain the significant performance differences between control methods. In addition, specific cases are carried out to quantify the influence of F_T . The chapter concludes with our own performance analysis of the control methods to directly evaluate their effectiveness in wake recovery.

4.1 Baseline control

We begin by analyzing the BL case, which serves again as the reference for all subsequent control methods. The objective is to explain the vortical structures observed earlier by examining the velocity field in the wake. The analysis is conducted in cylindrical coordinates, whose reference frame is shown in Figure 4.1, as this system is better suited to describe the flow in the wake.

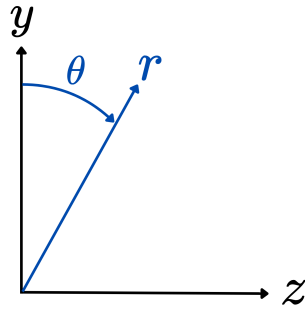


Figure 4.1: Definition of the cylindrical coordinate system

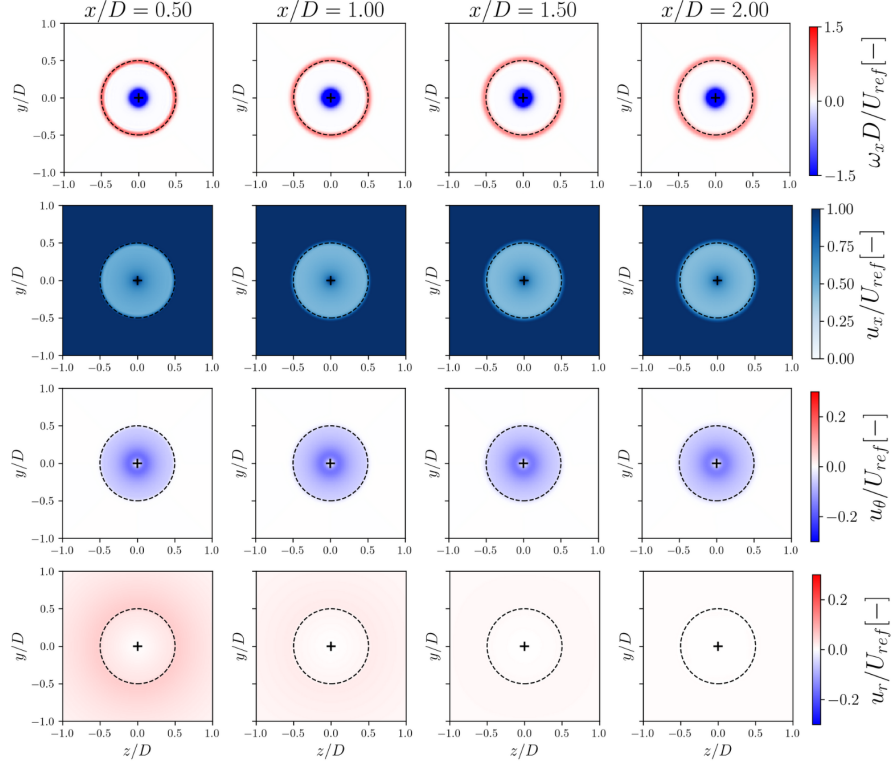


Figure 4.2: Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the baseline case at four downstream positions from $x/D = 0.5$ to $x/D = 2$.

Figure 4.2 presents the three velocity components as well as ω_x . We first observe a velocity deficit in u_x induced by F_N , and a swirling motion of the wake, illustrated by the presence of u_θ . The latter is induced by F_T and is negative, as the wake's swirling motion rotates CCW while the rotor rotates CW. Both u_r and u_θ fields are azimuthally uniform in the wake, directly reflecting the uniformity of the corresponding forces. The magnitude of u_r is small and decreases downstream.

The contribution to ω_x can be derived from Equation 3.8:

$$\omega_x = \frac{1}{r} \frac{\partial}{\partial r}(ru_\theta) - \frac{1}{r} \frac{\partial u_r}{\partial \theta} \quad (4.1)$$

In this case, since u_r is azimuthally uniform, the term $-\frac{1}{r} \frac{\partial u_r}{\partial \theta}$ vanishes, and ω_x originates only from u_θ . Specifically, it arises from the radial gradient $\frac{1}{r} \frac{\partial}{\partial r}(ru_\theta)$ between swirling and non-swirling regions, namely the hub and tip areas, thereby inducing hub and tip vorticity.

These features remain unchanged downstream, resulting in a non-deflected wake as shown in Figure 4.3. Moreover, the velocity deficit shows little recovery, which explains the poor performances of WTs positioned downstream. This highlights the need for effective wake recovery strategies.



Figure 4.3: Volume rendering of the vorticity field for a baseline-controlled wind turbine.

4.2 Static offset control

As the wake dynamics become more complex with IPC-based control strategies, the analysis will be divided into three distinct regions:

- **Near wake:** from $x/D = 0.25$ to $x/D = 1$
- **Mid wake:** from $x/D = 1.5$ to $x/D = 3$
- **Far wake:** from $x/D = 4$ to $x/D = 7$

4.2.1 Near wake region

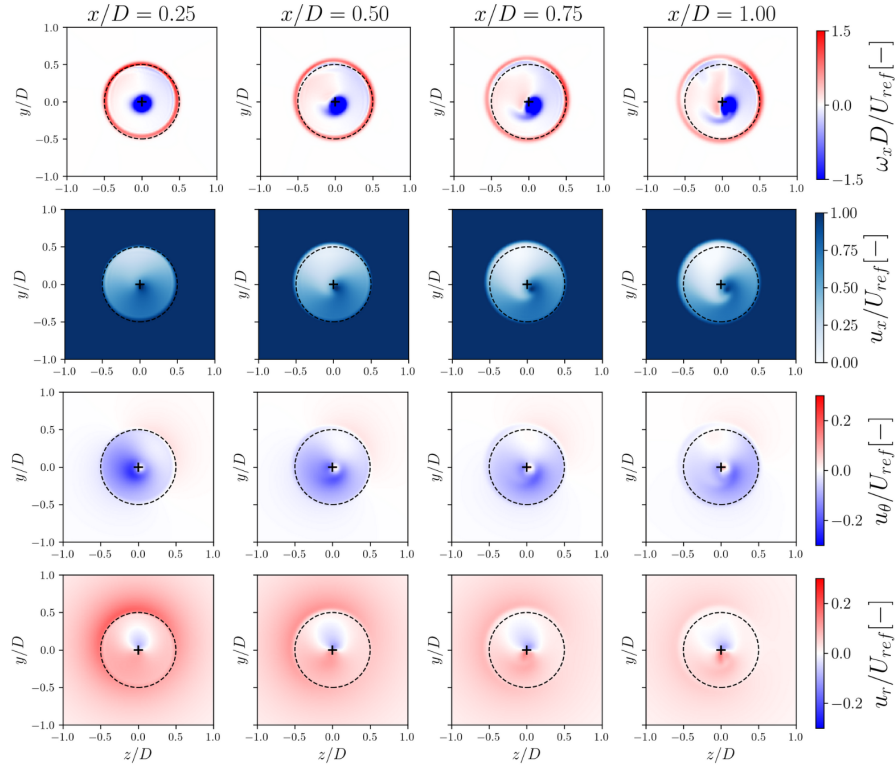


Figure 4.4: Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the static offset control at four downstream positions from $x/D = 0.25$ to $x/D = 1$.

As shown in Figure 4.4, which presents cross-flow slices of the near wake, the ST control significantly alters the wake behavior. The NUAD of F_N induced by the IPC generates a non-uniform u_x field at $x/D = 0.25$. This velocity deficit acts as a localized flow obstruction, forcing the surrounding fluid to bypass it as illustrated on Figure 4.5. As a result, additional velocity components are induced [35]:

- a radial component u_r , directed from regions of u_x deficit toward regions of u_x excess
- an azimuthal component u_θ , whose sign is positive for $0 < \theta < \frac{\pi}{2}$ and negative for $0 > \theta > \frac{-\pi}{2}$

This induces the presence of u_r inside the wake. The induced u_θ , superimposed on the pre-existing swirl in the wake, produces the overall u_θ distribution observed at $x/D = 0.25$.

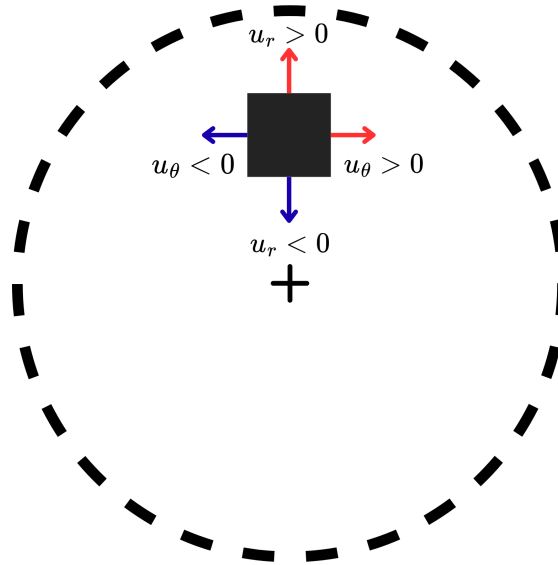


Figure 4.5: Illustration of the induced velocities generated by a flow obstruction

Both effects generate some $\frac{1}{r} \frac{\partial}{\partial r}(ru_\theta)$ and $-\frac{1}{r} \frac{\partial u_r}{\partial \theta}$ (see Equation 3.8), which contribute to the formation of vorticity inside the wake and explain the previously observed vorticity lobes.

Furthermore, the induced velocities cause the u_x deficit to propagate into the wake as it develops downstream. This is clearly visible at $x/D = 1.0$, where the u_x deficit occupies nearly three-quarters of the wake.

Looking at the vorticity evolution, two main effects can be identified. First, the hub vortex begins to rotate around the wake center, being displaced outward by the positive vorticity lobe. Second, between $x/D = 0.75$ and $x/D = 1.0$, the tip vorticity exhibits a noticeable loss of strength near the positive vorticity lobe.

4.2.2 Mid wake region

Let's dive into the mid-wake analysis, with cross-flow slices shown in Figure 4.6. We observe the formation of a negative vortex within the tip vorticity at $x/D = 1.5$, located in the region where tip vorticity had weakened. This vortex grows to form, at $x/D = 2.0$, a system of co-rotating vortex together with the hub vortex.

As studied in the literature [36], systems of co-rotating vortex pairs tend to merge. This behavior is also observed here, where the two vortex progressively merge from $x/D = 2.5$ to $x/D = 3$. Meanwhile, the u_x deficit continues to propagate as the wake evolves downstream.

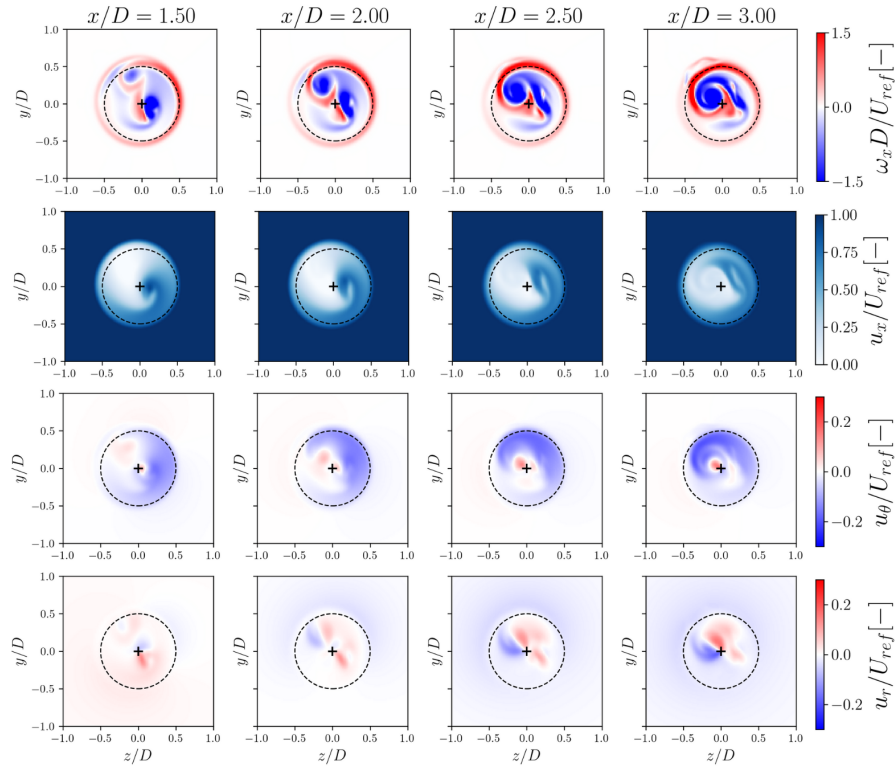


Figure 4.6: Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the static offset control at four downstream positions from $x/D = 1.5$ to $x/D = 3.0$.

4.2.3 Far wake region

Finally, as shown in Figure 4.7, the core negative vortex remains within the far wake and adopts a central position. This vortex is illustrated on the u_x fields (by a blue arrow). We observe that the vortex is localized at the same position as the u_x deficit, capturing it within its core.

This vortex is therefore detrimental to wake recovery, as it encapsulates the velocity deficit, explaining the poor performances of ST control. Moreover, the wake remains undeviated, as shown in Figure 4.8.

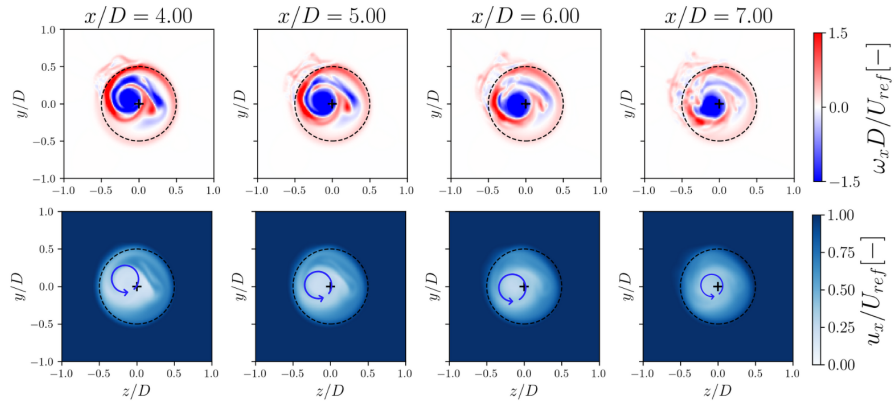


Figure 4.7: Averaged cross-flow slices of the streamwise vorticity ω_x and the streamwise velocity u_x , taken at $T_H = 1$, are shown for the static offset control at four downstream positions from $x/D = 4.0$ to $x/D = 7.0$.

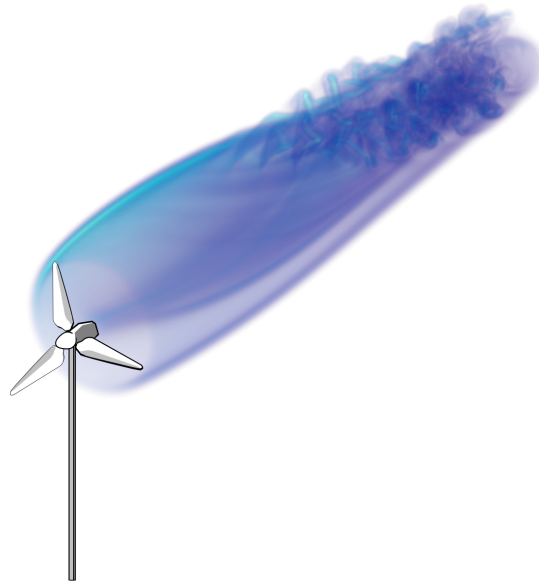


Figure 4.8: Volume rendering of the vorticity field for a static-offset controlled wind turbine.

4.3 CW helix control

We now turn to the control methods of interest: the helix control. Compared to the ST case, the dynamics are more complex due to the unsteady nature of the imposed perturbation.

For instance, with CW helix control, the CW rotation of the force distribution produces a CW temporal rotation of the wake structures when observed at a fixed cross-flow position. However, as the wake is convected downstream, this temporal motion is mapped into space, causing the spatial structure of the wake to wrap in the opposite direction, resulting here in a CCW helical geometry.

This distinction between temporal rotation and spatial helical wrapping, illustrated in Figure 4.9, is essential to correctly interpret the wake dynamics and avoid potential misinterpretations.

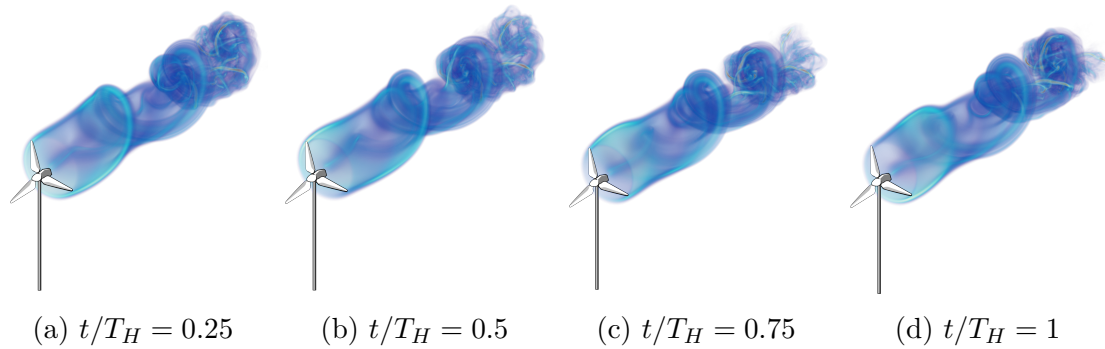


Figure 4.9: Volume rendering of the vorticity field for a CW helix-controlled wake, shown at four time steps corresponding to quarters of the helix period T_H .

4.3.1 Near wake region

Figure 4.10 presents wake structures induced by CW helix control. In this configuration, the NUAD of F_N also induces a corresponding u_x deficit in the near wake. However, this deficit is not stationary; it follows the spatial development of the wake and exhibits the same CCW rotation.

An important observation here is that the u_x deficit induces u_θ and u_r velocity fields that are not perfectly aligned with the deficit itself (as it was for the ST case). This misalignment might be interpreted as a phase lag: the induced velocity observed at $x/D = 0.25$ results from the deficit at a slightly earlier time, leading to a small angular offset of $\theta = -\pi/4$ as the wake rotates CW in time.

This small difference has a significant impact on the evolution of the wake. In this case, the u_x deficit does not propagate downstream in the same manner as in the ST case, but instead mixed with adjacent regions of u_x excess.

This interaction amplifies the induced velocity, as the u_θ and u_r fields exhibit much higher magnitudes at $x/D = 1.0$ compared to $x/D = 0.25$. Notably, u_θ even attains positive values, indicating a localized reversal in the swirl direction.

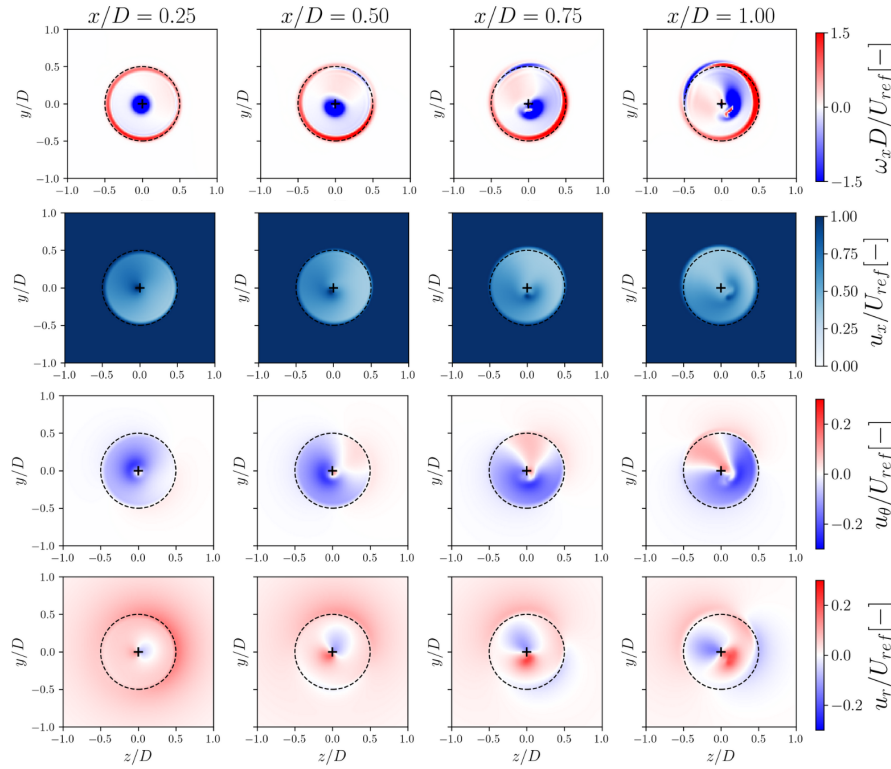


Figure 4.10: Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the CW helix case at four downstream positions from $x/D = 0.25$ to $x/D = 1.0$.

All these effects influence the vorticity field, which initially exhibits the same two-lobe structure as in the ST case but then follows a significant different evolution. Indeed, the positive vorticity lobe pushes the hub vortex outward, causing it to spread azimuthally. The tip vorticity is also weakened, even becoming locally negative near the positive lobe at $x/D = 1.0$.

4.3.2 Mid wake region

The mid-wake behavior, illustrated in Figure 4.11, reveals further interesting dynamics. The hub vortex continues to spread, and the tip vorticity remains weakened at $x/D = 1.5$. Beyond $x/D = 2.0$, the remaining positive tip vorticity begins to roll up, and by $x/D = 2.5$ it forms a system of counter-rotating vortex (CVP) together with the hub vortex, as observed in previous studies [16, 37]. This CVP formation is accompanied by an enhanced u_r , increased radial displacement of the wake, and stronger mixing of the u_x deficit.

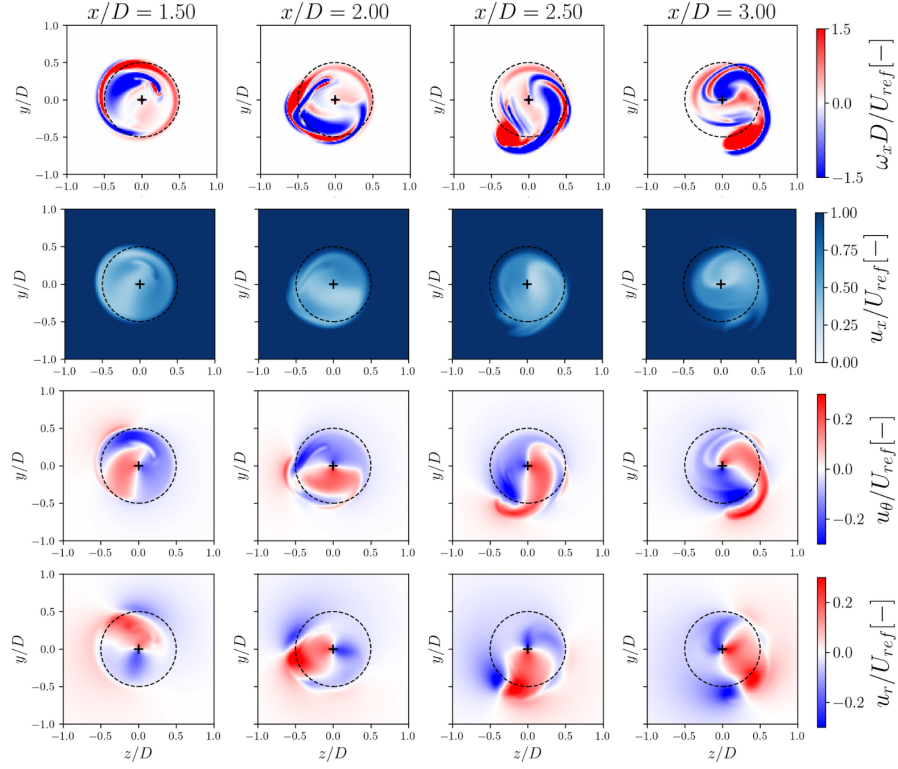


Figure 4.11: Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the CW helix case at four downstream positions from $x/D = 1.5$ to $x/D = 3.0$.

4.3.3 Far wake region

In contrast to the co-rotating vortices observed in the ST case, the CVP do not merge, as illustrated in Figure 4.10. Instead, it persist, evolve and rotate with the helix as it propagates downstream. This CVP plays a beneficial role in wake recovery [19].

Firstly, it induce a radial displacement of the wake, giving rise to the helical trajectory observed (see Figure 4.9). As a result, a downstream wind turbine would not be impacted by the full wake raising its performances.

Secondly, the CVP promotes the entrainment of outer flow into the wake (Indicated by the blue and red arrows on the u_x field) contributing to wake recovery. Nevertheless, their positioning is not optimal, and a portion of the u_x deficit remains trapped within their cores.

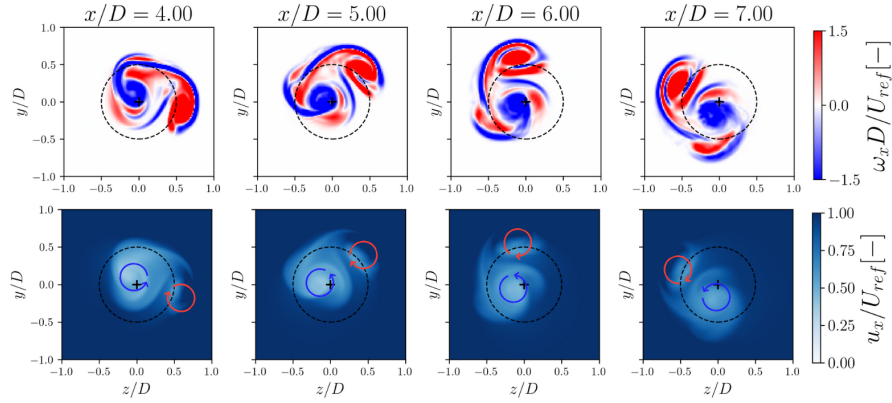


Figure 4.12: Averaged cross-flow slices of the streamwise vorticity ω_x and the streamwise velocity u_x , taken at $T_H = 1$, are shown for the CW helix case at four downstream positions from $x/D = 4.0$ to $x/D = 7.0$.

4.4 CCW helix control

As illustrated in Figure 4.13, the CCW helix control produces a wake with the same main features as the CW helix control, but with all rotations reversed. Specifically, the helix wraps in the CW direction while exhibiting a CCW temporal rotation.

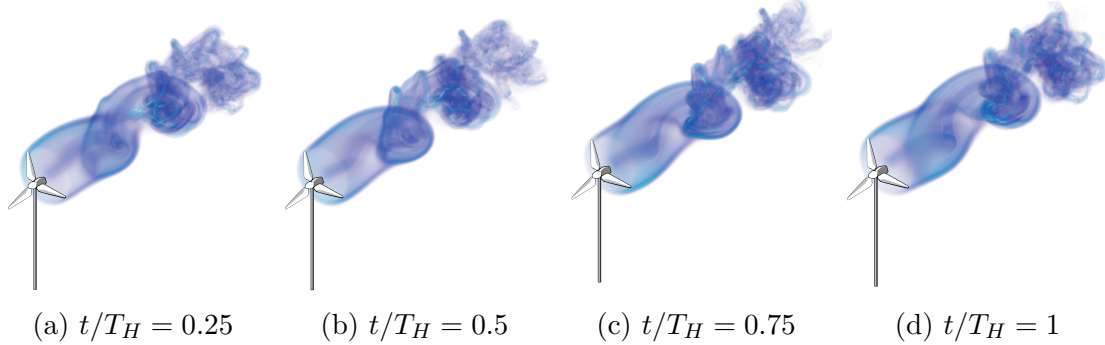


Figure 4.13: Volume rendering of the vorticity field of the CCW helix-controlled wake, shown at four time steps corresponding to quarters of the helix period T_H .

4.4.1 Near wake region

The initial wake presented in Figure 4.14 exhibits the same features as the previous cases at $x/D = 0.25$: a u_x deficit and the associated induced velocities. The difference lies in the phase lag of the induced velocities, which is reversed due to the opposite rotation of the wake.

This reversal modifies the subsequent evolution of the u_x field. In this case, as the wake develops, regions of u_x excess propagate differently than in the CW helix. This, in turn, alters the induced velocity patterns and the evolution of the vorticity lobes.

Focusing on the vorticity field, we observe that the hub vortex begins to rotate in the CW direction, occupying the position of the positive vorticity lobe. On the same side, the tip vorticity is also weakened and from $x/D = 0.75$, the negative lobe starts to strengthen at its extremity.

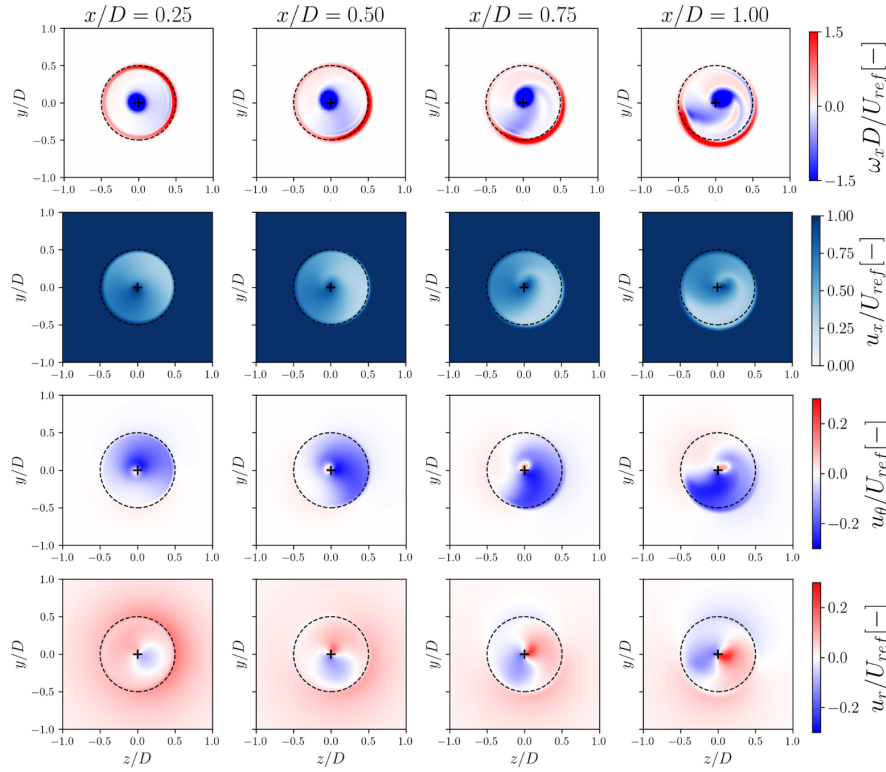


Figure 4.14: Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the CCW helix case at four downstream positions from $x/D = 0.25$ to $x/D = 1$.

4.4.2 Mid wake region

The negative vorticity lobe continues to strengthen in the mid wake region presented in Figure 4.15, forming a co-rotating vortex system with the hub vortex at $x/D = 1.5$. This newly formed vortex is progressively assimilated by the tip vorticity, which has also intensified by $x/D = 2.5$. At the same time, some negative tip

vorticity, already present at $x/D = 1.5$, progressively strengthens and begins to form a negative vortex close to the hub vortex at $x/D = 3.0$.

Examining the u_x field, the excess propagates in the wake up to $x/D = 2.0$. From this point onward, the wake exhibits significantly enhanced mixing, surpassing the efficiency observed in the CW helix control case.

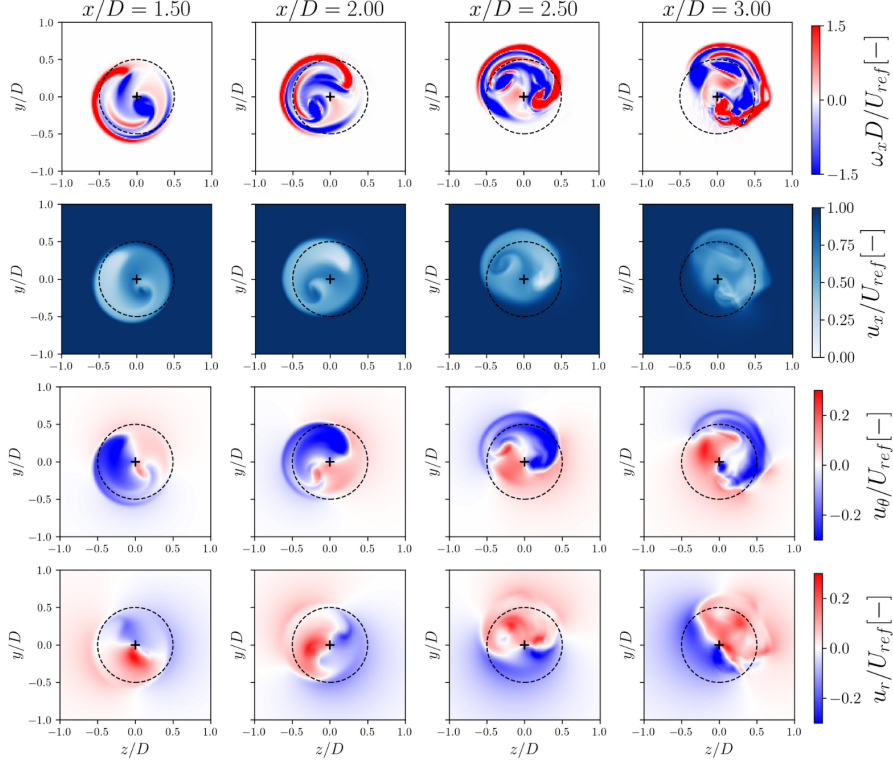


Figure 4.15: Averaged cross-flow slices of the streamwise vorticity ω_x and the three velocity components, taken at $T_H = 1$, are shown for the CCW helix case at four downstream positions from $x/D = 1.5$ to $x/D = 3.0$.

4.4.3 Far wake region

In the far wake shown on Figure 4.16, the two negative vortex have merged and now form, together with the positive vortex, a CVP. This CVP is again highly beneficial, as it injects momentum from the outer flow and enhances wake deflection.

Comparing the u_x field with the CW case in Figure 4.12, it is clear that the wake has recovered more effectively and shows greater deflection. This observation will be further confirmed in the performance assessment presented in Section 4.6.

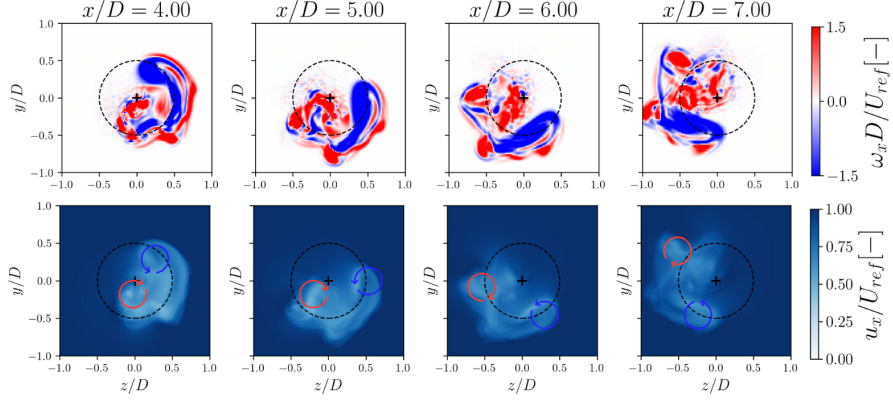


Figure 4.16: Averaged cross-flow slices of the streamwise vorticity ω_x and the streamwise velocity u_x , taken at $T_H = 1$, are shown for the CCW helix case at four downstream positions from $x/D = 4.0$ to $x/D = 7.0$.

We attribute this performance difference to the orientation of the CVP. As illustrated in Figure 4.17, the CVP generated by the CW helix primarily injects momentum in the azimuthal direction, whereas the CVP produced by the CCW helix is oriented to inject momentum more radially into the wake. This radial orientation enhances the effectiveness of momentum transfer into the wake, thereby improving recovery.

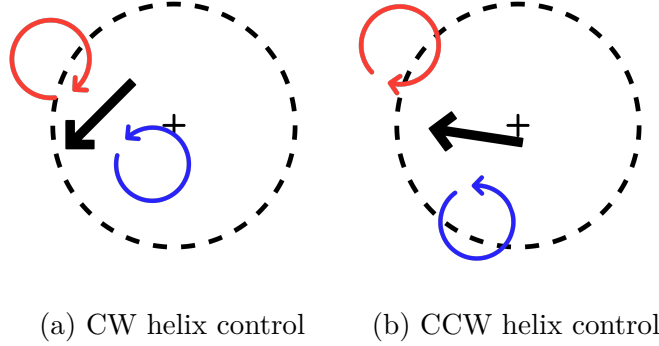


Figure 4.17: Illustration of the counter-rotating vortex pairs (CVP) formed in helix-controlled wakes.

4.5 Influence of the tangential force

As you may have noticed, the previous analysis of the wake did not mention the influence of the NUAD of F_T . This section aims to evaluate the hypothesis that it has no effect on the wake dynamics. In the second part, we will examine the

interaction between the swirl and helix control methods. To achieve this, we take advantage of the approximate model, which allows us to freely manipulate the forces in order to test various scenarios. For the sake of conciseness, we present here only the CCW helix control results. The corresponding analysis for the CW helix control can be found in Appendix B.

The first specific case we investigate considers the force distributions shown in Figure 4.18. Here, F_N is subjected to CCW helix control, while F_T is artificially kept unaffected by the control, thus showing a baseline-like distribution. This setup allows us to isolate and assess the impact of the NUAD of F_T , which is now absent.

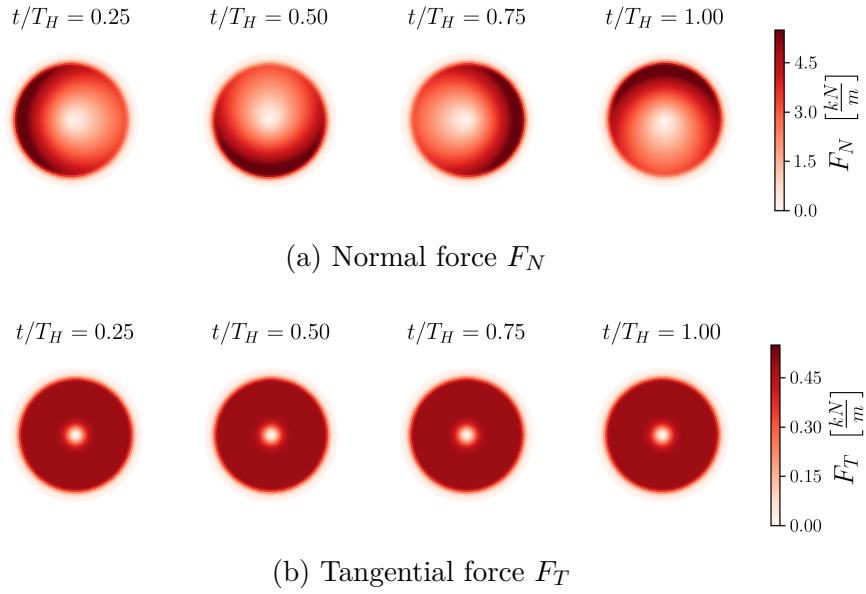


Figure 4.18: Force distributions over the AD at four time steps within one helix period T_H for the control case with CCW helix applied to F_N and uniform F_T .

Figure 4.19 shows the evolution of the wake structure for this particular case, compared to the reference CCW helix control, which features a NUAD of F_T . These results confirm our previous hypothesis: the NUAD of F_T induced by the IPC has no impact on wake dynamics and on the formation of the CVP. Indeed, the vorticity fields are essentially identical, with only minor discrepancies observed.

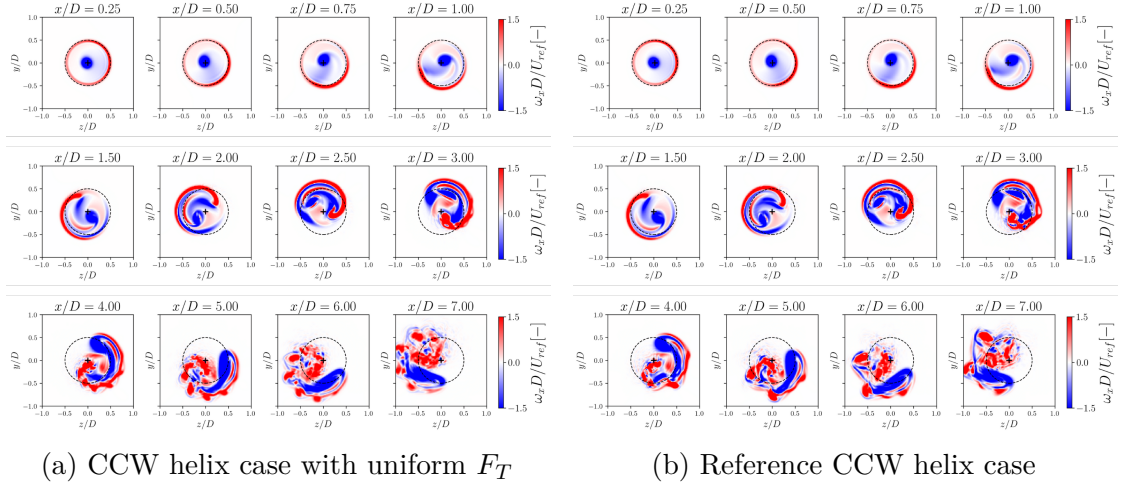


Figure 4.19: Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, for modified and reference CCW helix case.

However, F_T still contributes to the generation of the swirl responsible for the hub and tip vorticity. This swirl may interact with the helix control. To assess its contribution, we perform an additional case in which F_T is completely removed, as shown in Figure 4.20.

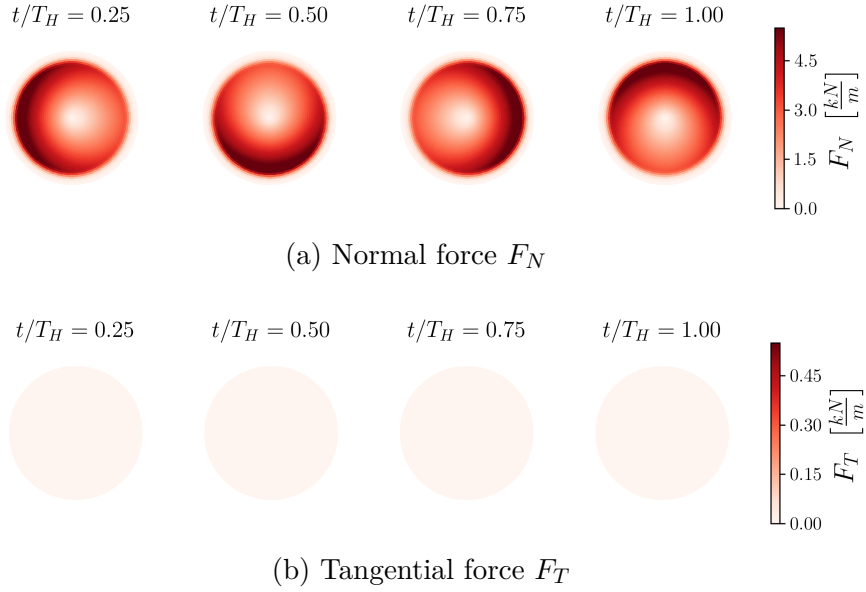


Figure 4.20: Force distributions over the AD at four time steps within one helix period T_H for the CCW helix control case without swirl

The evolution of the wake structure for this additional case is displayed in Figure 4.21, again in comparison with the reference CCW helix control.

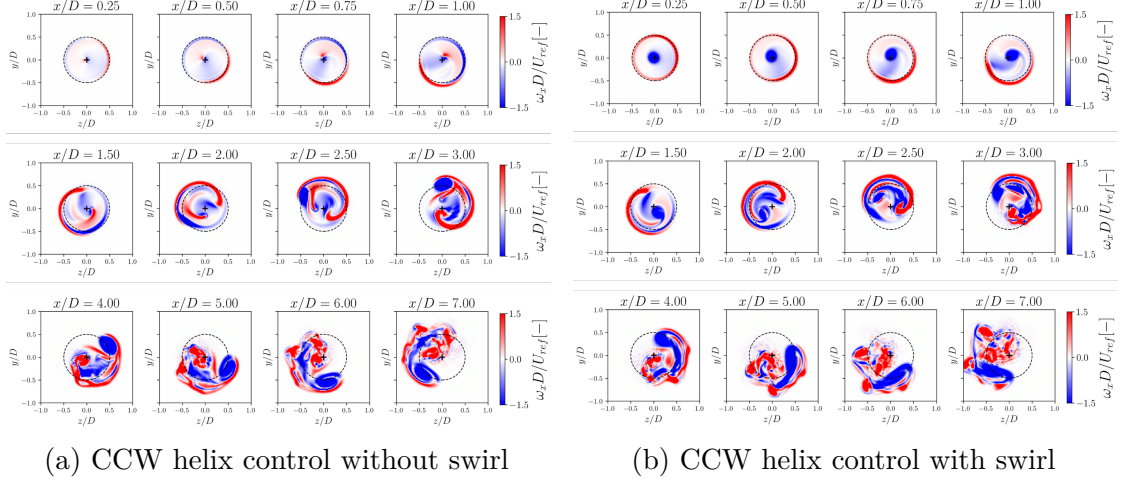


Figure 4.21: Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, for CCW helix case with and without swirl.

In the near wake, we observe exactly the same trend as before, except that the hub and tip vorticity are absent. The two lobes are still present, confirming that they originate solely from the induced velocity generated by the u_x deficit. These velocity fields in the near wake are displayed in Figure 4.22, which allows us to visualize the induced velocity field described previously.

However, these lobes are slightly weaker as they no longer superpose with the swirl, reducing the contribution of the term $\frac{1}{r} \frac{\partial}{\partial r}(ru_\theta)$ in the vorticity decomposition (see Equation 3.8). The wake evolution then follows the same overall pattern, except that the hub vortex is no longer present. Consequently, the final negative vortex is no longer a combination, but only the vortex formed in the tip vorticity.

Moreover, we observe that the CVP formed without swirl does not adopt a position similar to the one obtained with swirl. Instead, its orientation more closely resembles that observed in the CW helix case (see Figure 4.17), where momentum is injected predominantly in the azimuthal direction, resulting in poorer wake recovery.

These results confirm the experimental study of Gutknecht *et al.* [37], which shows that, without swirl, CW and CCW helix perform equivalently, suggesting an interaction between the helix and the swirl. Our findings indicate that this interaction likely involves the hub vortex generated by the swirl, which influences the formation of the CVP and shifts its orientation radially, thereby enhancing the performance of CCW helix.

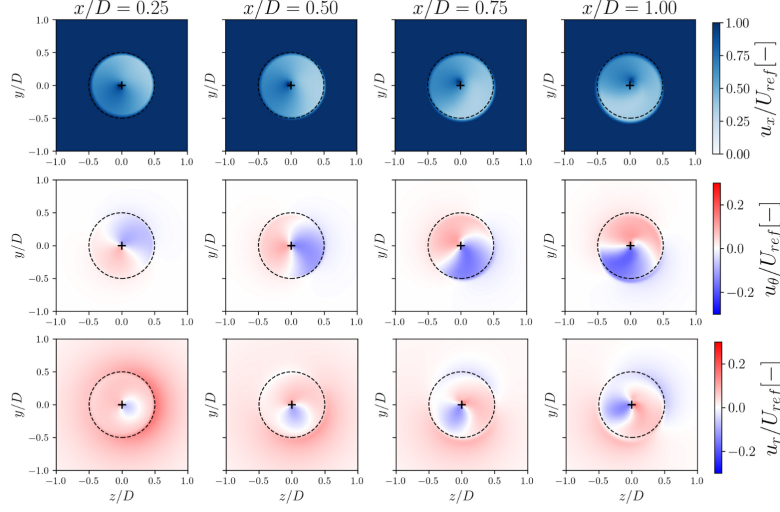


Figure 4.22: Velocity field of the CCW helix case without swirl

4.6 Performance assessment

To conclude and confirm the observations made on the wake dynamics, we now examine the performance of the different control methods. To quantify their effectiveness, we use two variables introduced by Coquelet *et al.* [16]. The first is the available power P_w , which represents the amount of power accessible to a wind turbine positioned downstream in the wake, calculated as follows:

$$P_w = \frac{1}{2} \rho \langle u_x^3 \rangle_{AD} \quad (4.2)$$

where $\langle \cdot \rangle_{AD}$ denotes the spatial average over the AD surface. P_w is normalized using the power of the upstream wind turbine $P_0 = \frac{1}{2} \rho U_{ref}^3 \pi \frac{D^2}{4}$. In this way we quantify how much the velocity deficit in the wake has recovered.

The second variable quantifies the wake deflection. The wake centerline position (y_{WCL}, z_{WCL}) is tracked in real time within the solver [38]. The radial displacement of the wake is then obtained as a time-averaged value:

$$r_{WCL}(x) = \frac{1}{T_H} \int_0^{T_H} \sqrt{(y_{WCL,p}(x, t))^2 + (z_{WCL,p}(x, t))^2} dt \quad (4.3)$$

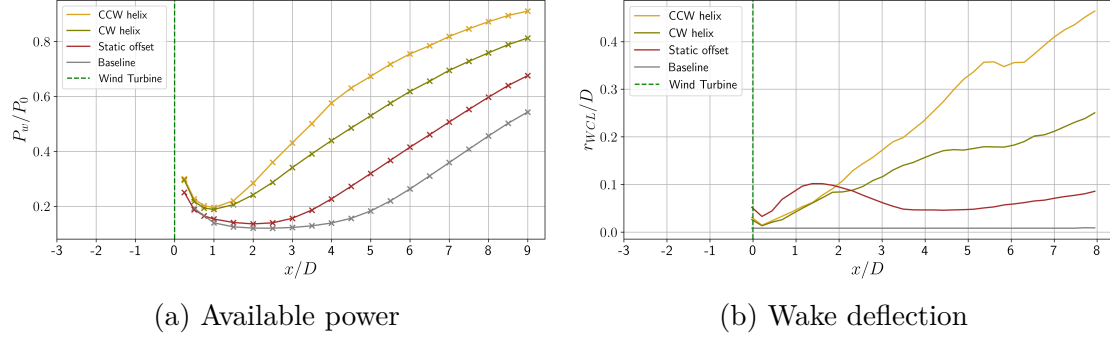


Figure 4.23: Performance comparison of the different control methods.

Figure 4.23 confirms the observations made on wake recovery. The ST case shows slightly better P_w than the BL case, whereas the helix control leads to a significant enhancement in wake recovery. A similar trend is observed for wake deflection: the BL produces no deflection, the ST achieves a small deflection, and the helix control methods succeed in deflecting the wake radially.

Finally, we confirm that the CCW helix outperforms the CW one, in agreement with findings reported in the literature. This result also supports our earlier observation that the CVP generated in the CCW case is more effective at enhancing wake recovery and deflection than the CVP produced in the CW case.

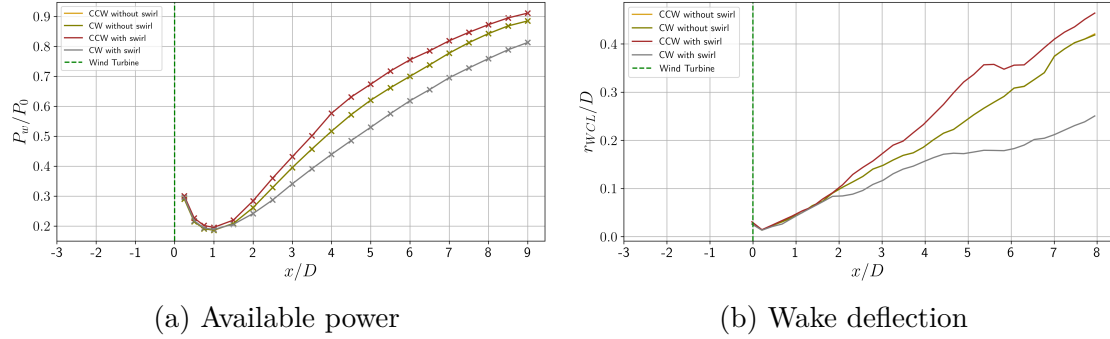


Figure 4.24: Performance comparison of the helix control methods with and without swirl.

Figure 4.24 presents the performance of the helix method with swirl and with the swirl artificially removed. We observe that both helix perform identically¹ without swirl, supporting the experimental results discussed previously [37]. This confirms that the interaction between the swirl and the CCW helix is responsible for the superior performance of the latter.

¹Curves are superposed

Chapter 5

Conclusion

5.1 Discussion

The objective of this Master's thesis was to analyze wind turbine wakes subjected to helix control methods. To achieve this, Large Eddy Simulations were performed using the simulation framework described in Chapter 2, which was further refined in Chapter 3 by simplifying the IPC-induced forces, enabling a clearer interpretation of the wake dynamics.

Chapter 4 investigated the different control strategies with the goal of understanding the mechanisms governing the wake dynamics. We first observed that the IPC-induced non-uniform normal forces generate a corresponding non-uniform streamwise velocity field. This results in regions of both axial velocity deficit and excess, where the deficit acts as an obstacle in the wake, inducing radial and azimuthal velocities.

The positions of these induced velocities relative to the velocity deficit vary depending on the helix control case, leading to distinct evolutions of the wake structures for the two helix directions. Although the structures evolve in a complex manner, they ultimately result in the formation of a counter-rotating vortex pair (CVP) in both helix control strategies. This CVP is responsible for the enhanced wake recovery and radial deflection reported in the literature and further confirmed by our analysis.

We attribute the performance differences between CW and CCW to the relative positioning of the CVP. In the CCW case, the CVP injects momentum predominantly in the radial direction, whereas in the CW case, the momentum is mainly injected azimuthally.

Finally, our results indicate that the IPC-induced tangential force distribution does

not influence the formation of the CVP, which develops regardless of its presence. Rather, its influence lies in modifying the CVP orientation. Specifically, the swirl generated by this force gives rise to a hub vortex that interacts with the formation of the CVP in the CCW helix, shifting its orientation. In contrast, in the CW helix, this interaction differs, leaving the CVP orientation unchanged and thereby explaining the superior performance of the CCW helix.

5.2 Perspectives

A first direct follow-up of this work would be to gain a better understanding of the vortex generated in the tip vorticity, which contributes to the formation of the CVP, and to quantify more precisely how this CVP contributes to enhanced performance.

This work has been performed under very simplified and idealized conditions to capture the essence of the helix control methods. It would be valuable to extend this study using a higher-fidelity solver that can model the tip vorticity more accurately and assess whether the interaction with these vortices is similar to that of the tip vortex sheet.

Finally, it would be interesting to confirm the formation of the CVP in realistic wind conditions, where a wind turbine operates with turbulent inflow, to assess the relevance of these findings in practical scenarios.

Appendix A

Domain size optimisation

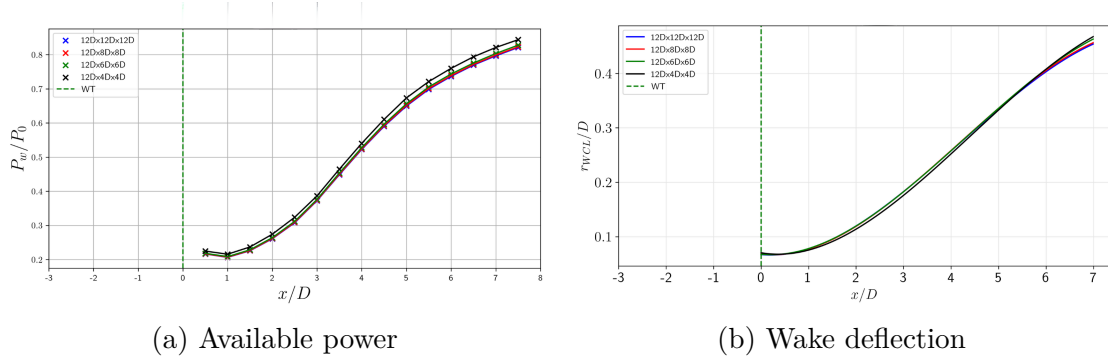


Figure A.1: Comparison of performance for different domain sizes.

To reduce computational cost, we chose to decrease the domain size in both the y and z directions. To ensure that this reduction does not significantly impact the wake, we examined the wake variables presented in Section 4.6, as they provide a good representation of the overall wake behavior.

Figure A.1 visually demonstrates that the effect of reducing the domain is minimal for both the P_w and the wake deflection. Table A.1 quantifies the relative error in available power between the original domain size $12D \times 12D \times 12D$ and the reduced domain sizes.

The relative error remains low until a domain size of $12D \times 4D \times 4D$, where it reaches 3.18%. We therefore selected this domain size as a compromise, ensuring that the wake behavior is not significantly altered while reducing computational resources.

Domain size	Relative error [%]
$12D \times 8D \times 8D$	0.37
$12D \times 6D \times 6D$	0.78
$12D \times 4D \times 4D$	3.18

Table A.1: Relative error in available power downstream for different domain sizes compared to the reference domain $12D \times 12D \times 12D$.

Appendix B

Influence of tangential force in CW helix

This appendix presents the analysis of the impact of F_T in the CW helix control case. The methodology follows the same approach as in Section 4.5.

The first scenario investigates the influence of the IPC-induced F_T on the wake by artificially removing it, as illustrated in Figure B.1.

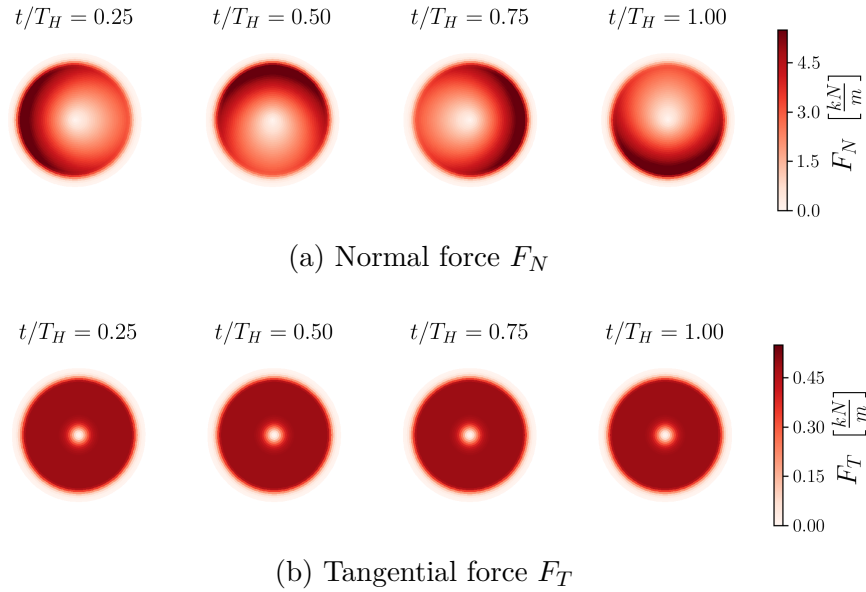
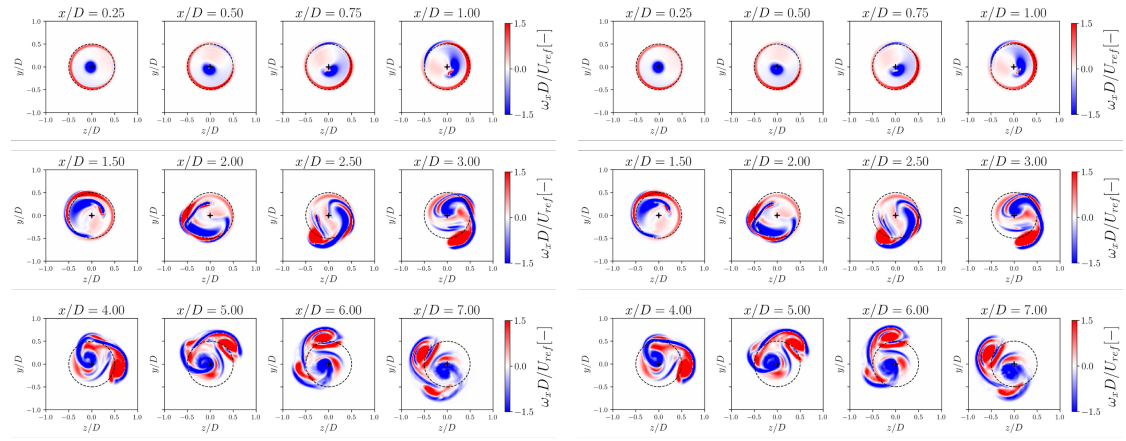


Figure B.1: Force distributions over the AD at four time steps within one helix period T_H for the control case with CW helix applied to F_N and uniform F_T .

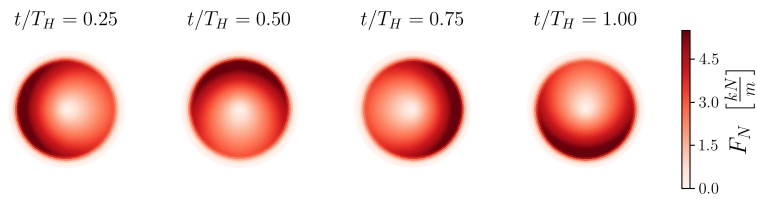
We observe in Figure B.2 that this change does not significantly alter the wake structure evolution, showing a trend similar to the CCW helix.. The NUAD of F_T generated by the IPC does not contribute to the formation of the CVP.



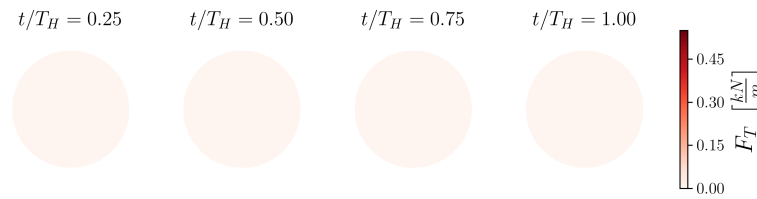
(a) CW helix control with uniform F_T

(b) Reference CW helix control

Figure B.2: Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, for modified and reference CW helix control.



(a) Normal force F_N



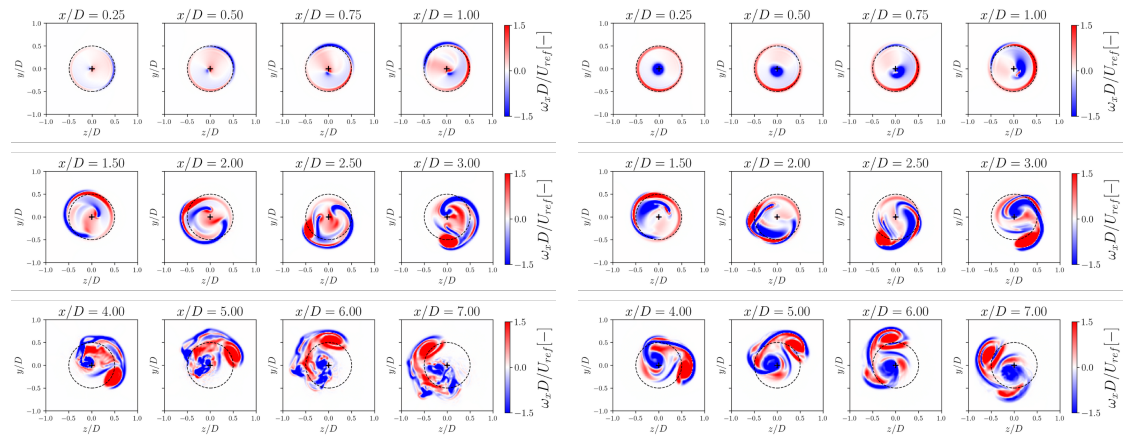
(b) Tangential force F_T

Figure B.3: Force distributions over the AD at four time steps within one helix period T_H for the CW helix control case without swirl.

The other scenario considers removing the swirl by setting F_T to zero, as presented in Figure B.3. The absence of swirl implies that the hub and tip vortices are no longer present.

Nevertheless, this does not alter the overall evolution of the wake, which still develops in the same way and leads to the formation of the CVP, as shown in Figure B.4.

Similar to the CCW case, the lack of a hub vortex results in a less pronounced final negative vortex within the CVP. In this configuration, however, the presence or absence of the hub vortex does not affect the CVP orientation, which remains equivalent with and without swirl.



(a) CW helix control without swirl

(b) CW helix control with swirl

Figure B.4: Averaged cross-flow slices of the streamwise vorticity ω_x , taken at $T_H = 1$, for CW helix control with and without swirl.

Bibliography

- [1] Marion Coquelet. *Numerical investigation of wind turbine control schemes for load alleviation and wake effects mitigation*. PhD thesis, UCLouvain, École Polytechnique de Louvain, Belgium, 2022. Prom. : Chatelain, Philippe ; Bricteux, Laurent.
- [2] Maud Moens. *Large eddy simulation of wind farm flows: improved Actuator Disk model and investigations of wake phenomena*. PhD thesis, UCLouvain, Ecole Polytechnique de Louvain, Belgium, September 2018. Prom. : Chatelain, Philippe ; Winckelmans, Grégoire.
- [3] J Jonkman, S Butterfield, W Musial, and G Scott. Definition of a 5-mw reference wind turbine for offshore system development. Technical report, National Renewable Energy Lab. (NREL), Golden, CO (United States), 02 2009.
- [4] *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland, 2023. [Core Writing Team, H. Lee and J. Romero (eds.)].
- [5] Directorate-General for Energy European Commission. Report from the commission to the european parliament and the council on progress of clean energy competitiveness. Technical report, October 2020.
- [6] IEA. World energy outlook 2024. IEA, Paris, 2024.
- [7] Daniel R. Houck. Review of wake management techniques for wind turbines. *Wind Energy*, 25(2):195–220, 2022.
- [8] Daan van der Hoek, Stoyan Kanev, Julian Allin, David Bieniek, and Niko Mittelmeier. Effects of axial induction control on wind farm energy production - a field test. *Renewable Energy*, 140:994–1003, 2019.

-
- [9] Michael Howland, Sanjiva Lele, and John Dabiri. Wind farm power optimization through wake steering. *Proceedings of the National Academy of Sciences*, 116:201903680, 07 2019.
 - [10] Ervin Bossanyi. Combining induction control and wake steering for wind farm energy and fatigue loads optimisation. *Journal of Physics: Conference Series*, 1037(3):032011, jun 2018.
 - [11] Daniel R. Houck. Review of wake management techniques for wind turbines. *Wind Energy*, 25(2):195–220, 2022.
 - [12] Wim Munters and Johan Meyers. Dynamic strategies for yaw and induction control of wind farms based on large-eddy simulation and optimization. *Energies*, 11(1):177, 2018.
 - [13] Wim Munters and Johan Meyers. Towards practical dynamic induction control of wind farms: Analysis of optimally controlled wind-farm boundary layers and sinusoidal induction control of first-row turbines. *Wind Energy Science*, 3:409–425, 2018.
 - [14] Joeri A. Frederik, Bart M. Doekemeijer, Sebastiaan P. Mulders, and Jan-Willem van Wingerden. The helix approach: Using dynamic individual pitch control to enhance wake mixing in wind farms. *Wind Energy*, 23(8):1739–1751, 2020.
 - [15] E Taschner, AAW van Vondelen, R Verzijlbergh, and JW van Wingerden. On the performance of the helix wind farm control approach in the conventionally neutral atmospheric boundary layer. *Journal of Physics: Conference Series*, 2505(1):012006, may 2023.
 - [16] M Coquelet, J Gutknecht, JW Van Wingerden, M Duponcheel, and P Chatelain. Dynamic individual pitch control for wake mitigation: Why does the helix handedness in the wake matter? *Journal of Physics: Conference Series*, 2767(9):092084, jun 2024.
 - [17] Daan Van Der Hoek, Carlos Simão Ferreira, and Jan-Willem Van Wingerden. Experimental comparison of induction control methods for wind farm power maximization on a scaled two-turbine setup. *Journal of Physics: Conference Series*, 2767(9):092064, jun 2024.
 - [18] Brian De Vos, Bjorn M. Harder, Thomas A. Huisman, Jonas Gutknecht, and Jan-Willem Van Wingerden. Mimicking the helix with a porous disc for wind tunnel testing. *Journal of Physics: Conference Series*, 2767(9):092063, jun 2024.

-
- [19] H. Korb, H. Asmuth, and S. Ivanell. The characteristics of helically deflected wind turbine wakes. *Journal of Fluid Mechanics*, 965:A2, 2023.
- [20] Majid Bastankhah and Fernando Porté-Agel. Experimental and theoretical study of wind turbine wakes in yawed conditions. *Journal of Fluid Mechanics*, 806:506–541, 2016.
- [21] Miltiadis Papalexandris. *Combustion and Fuels*. Presses Universitaires de Louvain, Louvain-la-Neuve, 2024.
- [22] M. Duponcheel. *Direct and large-eddy simulation of turbulent wall-bounded flows – Further development of a parallel solver, improvement of multi-scale subgrid models and investigation of vortex pairs in ground effects*. Phd thesis, Faculté des Sciences Appliquées, Université catholique de Louvain, October 2009.
- [23] Oleg V. Vasilyev. High order finite difference schemes on non-uniform meshes with good conservation properties. *J. Comput. Phys.*, 157(2):746–761, January 2000.
- [24] Moon J. Lee, Byung Do Oh, and Young Bae Kim. Canonical fractional-step methods and consistent boundary conditions for the incompressible navier–stokes equations. *Journal of Computational Physics*, 168(1):73–100, 2001.
- [25] Francis H. Harlow and J. Eddie Welch. Numerical calculation of time-dependent viscous incompressible flow of fluid with free surface. *The Physics of Fluids*, 8(12):2182–2189, 12 1965.
- [26] {Martin Otto Laver} Hansen. *Aerodynamics of Wind Turbines: second edition*. Earthscan, 2 edition, 2008.
- [27] Jens Norkær Sorensen and Wen Zhong Shen. Numerical modeling of wind turbine wakes. *Journal of Fluids Engineering*, 124(2):393–399, 05 2002.
- [28] M. Moens, M. Coquelet, F. Trigaux, and P. Chatelain. Handling individual pitch control within an actuator disk framework: verification against the actuator line method and application to wake interaction problems. *Journal of Physics: Conference Series*, 2265(2):022053, may 2022.
- [29] M. Coquelet, M. Moens, M. Duponcheel, J.W. van Wingerden, L. Bricteux, and P. Chatelain. Simulating the helix wake within an actuator disk framework: verification against discrete-blade type simulations. *Journal of Physics: Conference Series*, 2505(1):012017, may 2023.

-
- [30] J.J Monaghan. Extrapolating b splines for interpolation. *Journal of Computational Physics*, 60(2):253–262, 1985.
 - [31] Maud Moens, Matthieu Duponcheel, Grégoire Winckelmans, and Philippe Chatelain. An actuator disk method with tip-loss correction based on local effective upstream velocities. *Wind Energy*, 21(9):766–782, 2018.
 - [32] E. A. Bossanyi. Individual blade pitch control for load reduction. *Wind Energy*, 6(2):119–128, 2003.
 - [33] {Robert Flemming} Mikkelsen. *Actuator Disc Methods Applied to Wind Turbines*. PhD thesis, January 2004.
 - [34] J. Gutknecht, E. Taschner, M. Coquelet, A. Viré, and J. W. van Wingerden. The impact of coherent large-scale vortices generated by helix active wake control on the recovery process of wind turbine wakes. *Physics of Fluids*, 37(6):067162, 06 2025.
 - [35] Sidi Yousfi and Aliane Khaled. Turbulent flow around obstacles: Simulation and study with variable roughness. *International Journal of Heat and Technology*, 39:1659–1666, 10 2021.
 - [36] Ch. Josserand and M. Rossi. The merging of two co-rotating vortices: a numerical study. *European Journal of Mechanics - B/Fluids*, 26(6):779–794, 2007.
 - [37] Jonas Gutknecht, Daniel Van Den Berg, Daan Van Der Hoek, Brian De Vos, Bjorn Harder, Axelle Viré, and Jan-Willem Van Wingerden. Wake recovery enhancement with helix active wake control: Vortex structures in a porous disk wake observed in piv experiments. *Journal of Physics: Conference Series*, 3016(1):012030, may 2025.
 - [38] N Coudou, M Moens, Y Marichal, J Van Beeck, L Bricteux, and P Chatelain. Development of wake meandering detection algorithms and their application to large eddy simulations of an isolated wind turbine and a wind farm. *Journal of Physics: Conference Series*, 1037(7):072024, june 2018.

UNIVERSITÉ CATHOLIQUE DE LOUVAIN

École polytechnique de Louvain

Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | www.uclouvain.be/epl