

École polytechnique de Louvain

Simulation of a helicopter in Vortex Ring State through a coupled simulation of multi-body dynamics and aerodynamics

Author: **Geoffrey CHAIDRON**

Supervisors: **Philippe CHATELAIN, Matthieu DUPONCHEEL, Grégoire WINCKELMANS**

Reader: **Miltiadis PAPALEXANDRIS**

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This thesis represents the biggest work I have done in my life so far. It wasn't an easy way, full of hesitations and misunderstandings. But I went through them, pushed by my passion for the aeronautical domain.

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Introduction

In one century of existence, helicopters have become a must-have equipment for lot of domains due to their natural ability to move vertically. In civil applications, one can cite: the coast guards that must operate in stormy seas, where boating is too dangerous; the mountain rescuers that must go as fast as possible on terrains that are nearly unreachable with ground vehicles, and where airplanes cannot land; some deliveries - often humanitarian - must be done in remote lands where only helicopters can go; and so more. In military operations, helicopters allow to go on a contested territory to bring soldiers or provisions safely in comparison to parachuting them.

But those fascinating machines are incredibly complex and can get in some serious situations. One of them is called the *vortex ring state (VRS)*. This is an extremely dangerous flight regime that happen in rapid descend, resulting in a huge loss of altitude and that cannot be escaped anyhow. Multiple accidents have been caused by VRS. We can cite the *Marana incident* where a *V-22 Osprey* lost control in year 2000[1], killing all the passengers. Another example: during the famous *Operation Neptune Spear*, a modified *UH-60 Black Hawk* fell down, swept away by a VRS[2]. Fortunately, this crash wasn't lethal. A more recent accident is the crash of a *Bell 429* of the company *Mercy Flight* that happened in 2022, killing the pilot and his instructor[3].

In order to improve air safety, one should want to study this strange phenomenon. But studying it in real operation raises some concerns: firstly, since VRS happen at high descend rates (about $10m/s$, as we will see), they result in a huge loss of altitude, which involve safety concerns and severe time limitations. Another problem is the lack of control of the environmental conditions. Finally, this flight regime is feared by pilots such that only few of them would take part to the exercise.¹

A studying tool that gets rid of these problems exists: the wind tunnel. Even if this tool has allowed big improvements in the understanding of VRS, it is not perfect either. Indeed, wind tunnels cannot change of velocity very quickly and are unable to react to the thrust produced by the rotor plane efficiently. But the 21st century came with a new kind of tool that permits an easier and deeper research: the computer. This tool enables to simulate VRS with nearly no constrain.

The goal of this thesis is to simulate VRS to study them. My predecessor for this subject, H. Van Vyve[4], successfully simulated the wind tunnel behavior on computer. But we need to go beyond. My goal is to observe how VRS form themselves and how measurable parameters are evolving at that moment. Firstly, I will briefly explain how helicopters fly in chapter 1. Next, in the second chapter, I will present the tools that will be used to perform the simulations. Thereafter, I will set the model in chapter 3, performing a hover. I will then explore the whole descend flight path in chapter 4. Finally, the fifth and last chapter will be a deep analysis of the VRS. The reference book, used as the main source, will be *Principle of helicopters aerodynamics* by J. Gordon Leishman[5].

¹I have spoken about my thesis with multiple helicopter pilots and two reactions were common: the first one was an obvious interest in the subject and the second one was something like “without me”. This illustrates how much pilots want to avoid it.

Chapter 1

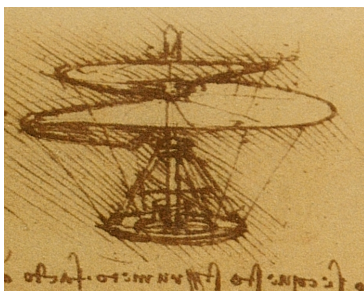
Flight dynamics of helicopters

In order to study and analyze the Vortex Ring State, it is important to understand how a helicopter works and how it evolves in its environment. This chapter will briefly explore the history of the helicopter and the key points of its flight behavior.

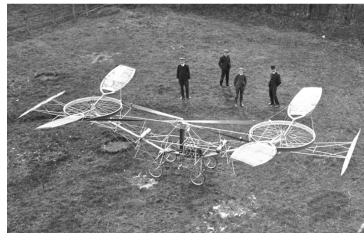
1.1 History of the helicopter

The idea of flying by lifting a body vertically is as old as the world itself. One can take the example of the *Aerial screw* [6] (figure 1.1a) which is 500 years old. We know nowadays that this screw could never have flown. Indeed, it is way too heavy and doesn't take in consideration the rotor-torque. But the idea was born. Due to technological reasons - mainly the lack of an engine with a high enough power to weight ratio, we have to wait until the 20th century for the first viable helicopters to appear.

The very first manned helicopter flight is attributed to Paul Cornu in 1907[5] (figure 1.1b). The helicopter he used was using a bi-rotor configuration and just succeeded to take off. We have to wait the 1930s to see the first 'real' helicopters and true flights. In the early 1940s, because of the need for WWII, the *Sikorsky R-4* (figure 1.1c) became the first mass produced helicopter [5]. In less than a century, helicopters have become a necessity and are widely used for their natural capacity to hover, helping for taking off in very small fields and to carry cargo where cranes can't go.



(a) da Vinci's aererial screw [6]
©Leonardo da Vinci



(b) Cornu helicopter [7]
©



(c) Sikorsky R-4 [8]
©USAAF

Figure 1.1: Early designs

1.1.1 Type of helicopters

One can cite hundreds of different helicopters, but we will end up with five distinctive configurations [5]:

1. The **conventional** configuration (figure 1.2), with one main rotor and one tail rotor, that is to be found on the wide majority of helicopters;
2. The **side by side** configuration (figure 1.3a), with two main rotors placed on the side of the helicopter;
3. The **tandem** configuration (figure 1.3b), with two main rotors placed in front and aft of the helicopter;
4. The **co-axial** configuration (figure 1.3c), with two main rotors placed one above the other;
5. And the **intermeshing** configuration (figure 1.3d), with two main rotors intersecting with each other.

Due to the drag force on the blades, a rotor produces torque around its axis. To counterbalance this torque, one needs to apply an opposite torque. On all the bi-rotor configurations, it suffices to make the rotors turn in opposite directions. On single-rotor configuration however, one has to add a tail rotor that blows on the side. This tail rotor represents a pure loss of energy, but the added weight and complexity of the bi-rotor configurations make the conventional one more accessible.



(a) Airbus H160 [9]
©Airbus



(b) Robinson R44 [10]
©Alan Radecki



(c) NHIndustries NH90 [11]
©Geoffrey Chaidron

Figure 1.2: Conventional configuration



(a) Bell-Boeing V22[12]
©The Boeing Company



(b) Boeing CH47[13]
©The Boeing Company



(c) Kamov Ka50 [14]
©Dmitriy Pichugin



(d) Kaman K-max [15]
©George Melendez

Figure 1.3: Unusual configurations

From left to right: side by side, tandem, co-axial and intermeshing

1.2 Mechanical principles

In this thesis, we will only focus on the conventional configuration, and more particularly on the *Airbus helicopter H135*, previously known as the *Eurocopter EC-135* [16]. It is represented on figure 1.4.

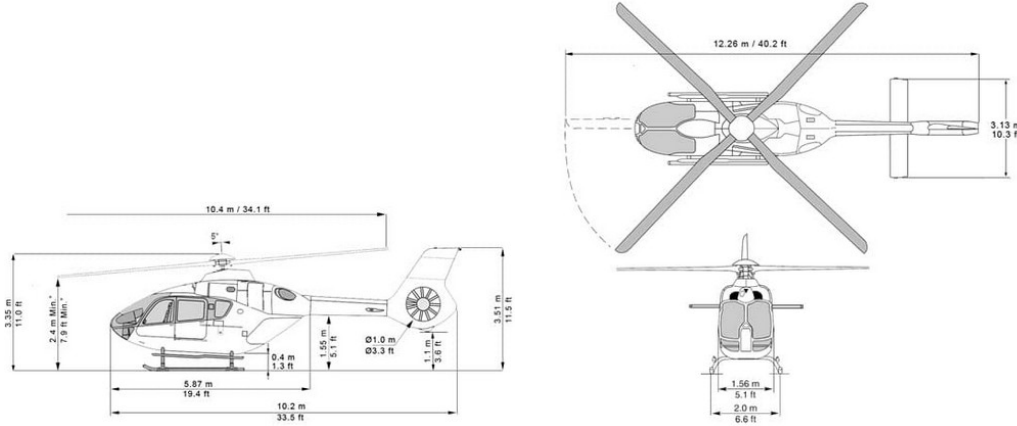


Figure 1.4: Airbus Helicopter H135
©Airbus

1.2.1 General principle

The idea behind helicopters is to take off directly thanks to the thrust produced by its engine(s). The lifting force of a helicopter is thus simply equal to the thrust it produces. In opposition to airplanes that are lifted thanks to their wings, helicopters are thus unable to glide.

A conventional helicopter consists of one main rotor, parallel to the ground or slightly inclined forward, directly driven by its engine(s). This rotor is composed of two or more blades, rotating around the same axis. Each of these blades basically works as an aircraft wing. They are indeed shaped like an airfoil which produces lift upward thanks to the pressure gradient produced by the velocity difference above and under it. This difference of velocity is due to the longer path the air has to take on the upper part of the airfoil because of a certain angle of attack. This force is represented on figure 1.5a¹.

The biggest difference with an aircraft wing is that, because of its turning behavior, the velocity of a blade varies strongly from the hub to the tip as illustrated in section 1.3. This leads to a more complex behavior of the flow dynamic which is absolutely not 1D.

As all airfoils, a helicopter blade also produces drag in the direction opposed to its displacement. This direction being circularly arranged around the helicopter, the drag force results in a torque that forces the helicopter to turn in the opposite direction. To counter-balance it, one puts a tail rotor, producing a matching torque, permitting the helicopter to be at equilibrium. This is illustrated in figure 1.5b. As this tail rotor does not participate in the lifting of the helicopter, it thus represents a pure loss of energy. However, it allows a very easy control of the yaw and is technologically simple and reliable.

¹Note: on this figure, 'A' stands for the angle of attack

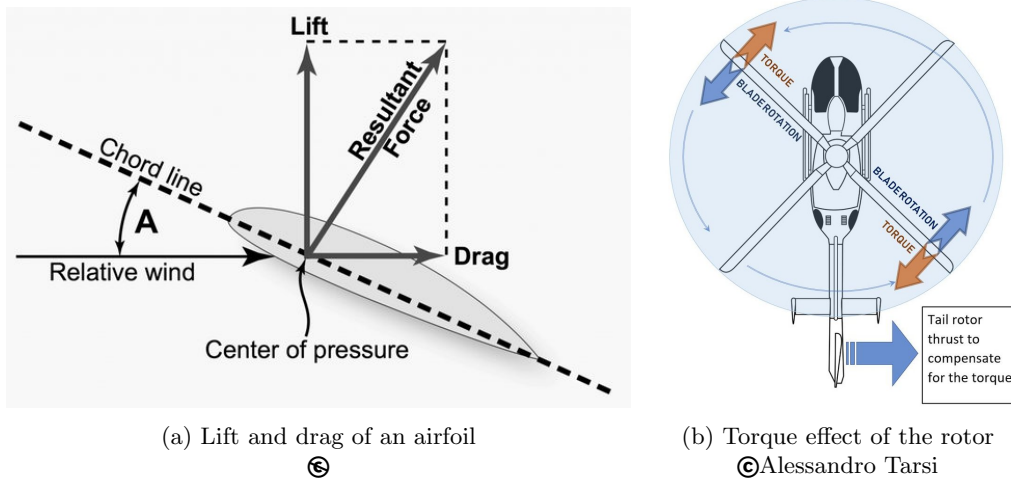


Figure 1.5

1.2.2 Main rotor description

Each blade of the rotor is attached to a hub, centered on the axis of rotation, such that the length of the blade plus the radius of the hub equals the rotor radius R . To describe the position of the blade, we define 4 angles:

- **The azimuth angle ψ** describes the position of the blade around the axis. We define $\psi = 0$ when the blade is toward the rear of the helicopter.
- **The flapping angle β** is the angle between the blade and the horizontal plane. We define $\beta > 0$ when the blade is above this plane.
- **The leading/lagging angle ζ** is the angle between the blade and the radial plane. We define $\zeta > 0$ when the blade is aft of this plane.
- **The pitch angle θ** (sometime referred as *feathering angle*) is the angle between the chord and the horizontal plane. We define $\theta > 0$ when the leading edge is above the plane.

The azimuth angle is represented on figure 1.7. β , ζ and θ are referenced as *flapping*, *leading/lagging* and *feathering* on figure 1.6.

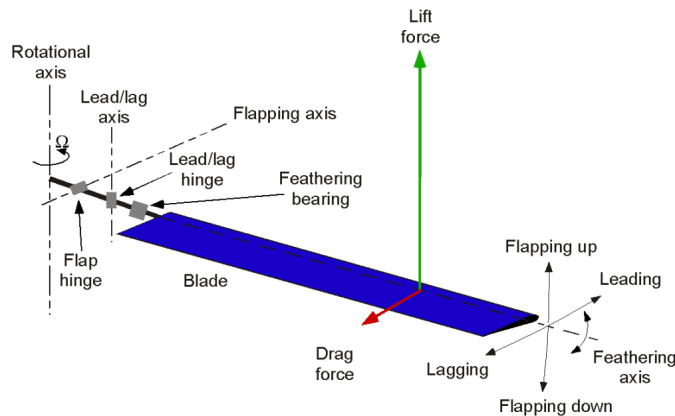


Figure 1.6: Flapping and lag angle

©[17]

1.2.3 Controls

To control its helicopter, a pilot can manage 5 parameters:

- The rotation speed ω ;
- The collective pitch θ_0 ;
- The two cyclic pitches θ_{1c} and θ_{1s} ;
- The tail rotor pitch θ_{TR} .

The rotation speed

Being directly linked to the turbine of the engine, the rotors are able to turn at different speeds. But, due to the inertia of the main rotor, this command is very slow and does not allow a direct control of the helicopter. This parameter is more useful as being changed between several flight regimes².

The collective command

The collective command acts on every blade at the same time. It allows to change the pitch angle θ of every blade by the same amount θ_0 . Increasing the collective pitch will immediately increase the thrust of the main rotor and vice-versa. This control is thus the most important for all vertical motions.

The cyclic command

The cyclic command acts on the longitudinal and lateral pitches θ_{1s} and θ_{1c} respectively. Modifying a cyclic pitch will have an opposite behavior on two sides of the rotor. For example, if we increase θ_{1c} the pitch of the blade that passes through the front will be reduced and the one passing through the aft will be increased, forcing the helicopter to incline itself forward. When being inclined, a part of the thrust will serve to push the helicopter forward (in our example), forcing him to move in that direction. The cyclic commands are thus the ones that permit the helicopter to be controlled in the directions parallel to the ground.

The collective and the cyclic pitches give us the total pitch that the blades have to take for every azimuth angle ψ :

$$\theta(\psi) = \theta_0 + \theta_{1c} \cos \psi + \theta_{1s} \sin \psi$$

The rudder

The rudder is the control of the yawing moment. It directly acts on the pitch of the tail rotor θ_{TR} , permitting to turn around the rotor axis. Let's note that this pitch also has to be influenced by the collective control since, when θ_0 increases, so does the drag and thus, the induced torque.

²Usually, pilots want a high rotation speed in the maneuvers near to the ground like the take-off and the landing since a higher ω leads to an increased reactivity of the other controls. But, when they are in cruise, they want to reduce ω to decrease the drag, and thus, enhance the efficiency.

1.3 Momentum theory

This section is mainly based on the section 2.2 of the reference book[5].

To study the behavior of a helicopter, it is important to learn the dynamics of a rotor. We will here consider that the blades evolve in a disk of radius R rotating at an angular velocity Ω . At the very center of the disk, the blades have a nil velocity and at the tip, they move at $V_{tip} = \Omega R$. The produced thrust varies with the square of the tip speed while the power varies with the cube of it, $T \propto V_{tip}^2$ and $P \propto V_{tip}^3$. These are represented on figure 1.7.

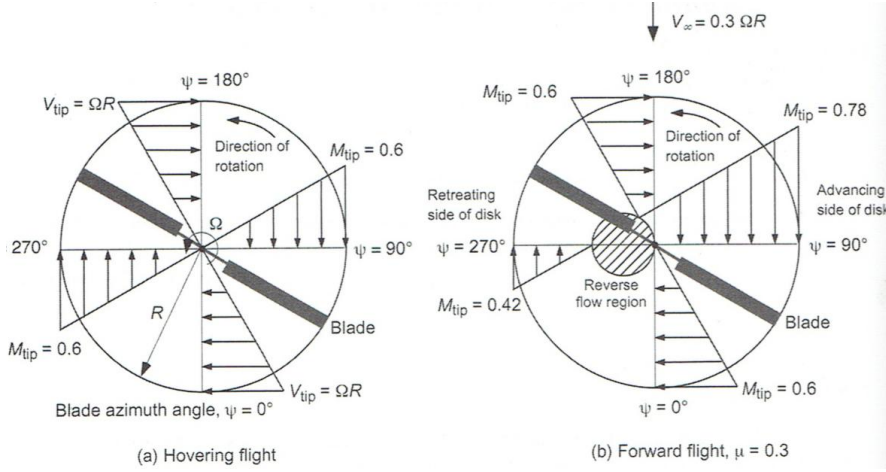


Figure 1.7: Velocity distribution

©[5]

In momentum theory, we use a control volume around the stream using the laws of conservation of mass, momentum and energy, respectively:

$$\iint_S \rho \vec{V} \cdot d\vec{S} = 0 \quad (1.1)$$

$$\vec{F} = \iint_S p d\vec{S} + \iint_S (\rho \vec{V} \cdot d\vec{S}) \vec{V} \quad (1.2)$$

$$W = \iint_S \frac{\rho \vec{V} \cdot d\vec{S}}{2} |\vec{V}|^2 \quad (1.3)$$

With S the surface of the control volume.

By making the assumption of a steady state and a quasi-1D incompressible flow, the mass flow rate is constant, such that:

$$\dot{m} = \iint_{\infty} \rho \vec{V} \cdot d\vec{S} = \iint_2 \rho \vec{V} \cdot d\vec{S} \quad (1.4)$$

$$= \rho A_{\infty} w = \rho A v_i \quad (1.5)$$

There are 4 interesting disk areas in our control volume. The far upstream plane is denoted 0, 1 is the plane just above the rotor, 2 is the plane just below the rotor and ∞ is the far wake. Let's call v_i the *induced velocity*, i.e. the velocity given to the flow by the rotor, w the velocity at the far wake and V_C the vertical velocity of the helicopter itself.

1.3.1 Hover

In the particular case of hover, the rotor is perfectly stationary. We have that $V_c = V_0 = 0$ as represented on figure 1.8. In this case, the thrust must be equal to the force on the fluid, from equations 1.2 and 1.4, this leads to:

$$T = \iint_{\infty} \rho (\vec{V} \cdot d\vec{S}) \vec{V} = \dot{m}w \quad (1.6)$$

Combining equations 1.5 and 1.6 gives us:

$$T = 2\rho A v_i^2 \iff v_h \equiv v_i|_{Hover} = \sqrt{\frac{T}{2\rho A}} \quad (1.7)$$

One can also show that the power is given by:

$$P = T \cdot v_i \quad (1.8)$$

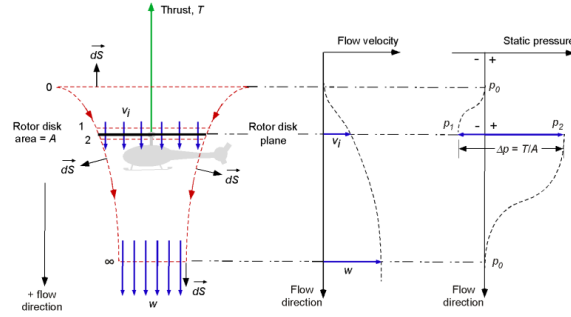


Figure 1.8: Flow model in hover configuration

©[17]

1.3.2 Ascending flight

We consider here a purely axial motion. There is thus no lateral flows and our control volume is still valid. In this case, $V_C > 0$, the velocity at the disk is thus $V_C + v_i$ as on figure 1.9. One can show that the equation 1.6 is still valid here such that:

$$T = \rho A (V_C + v_i) = 2\rho A (V_C + v_i) v_i \quad (1.9)$$

This equation can be derived to give:

$$\frac{v_i}{v_h} = \sqrt{\left(\frac{V_C}{2v_h}\right)^2 + 1} - \left(\frac{V_C}{2v_h}\right) \quad (1.10)$$

1.3.3 Descending flight

We are again in pure axial motion with, this time, $V_C < 0$. We can no more use our control volume. Indeed, if $V_C \ll 0$, the wake is no longer under the rotor but above it. This is the so-called *windmill state*. When $-2v_h < V_C < 0$, the things are even worse. The wake can be either under or above the rotor or even not well defined, following it in a very turbulent manner. In this region, the momentum theory cannot be applied as the assumptions made are not valid anymore. These regions are illustrated on figures 1.11 and 1.12.

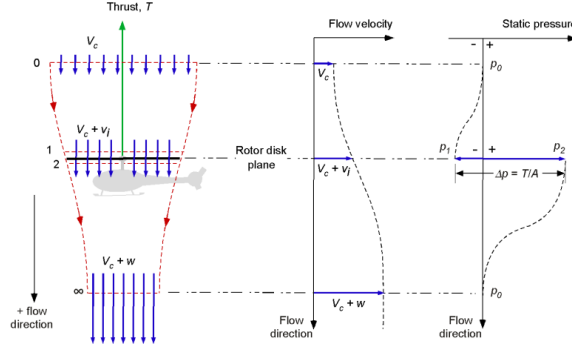


Figure 1.9: Flow model in ascending configuration

©[17]

Windmill brake State

To apply the momentum theory, we have to reverse our control volume, 0 now is the far upstream plane, far under the rotor. 1 and 2 are the under and above planes respectively and ∞ the far wake, far above the rotor. The velocity at the disk is thus $|V_C| - v_i$ as represented on figure 1.10. We have:

$$T = -\dot{m}w = -2\rho A(V_C + v_i)v_i \quad (1.11)$$

$$\frac{v_i}{v_h} = -\sqrt{\left(\frac{V_C}{2v_h}\right)^2 - 1} - \left(\frac{V_C}{2v_h}\right) \quad (1.12)$$

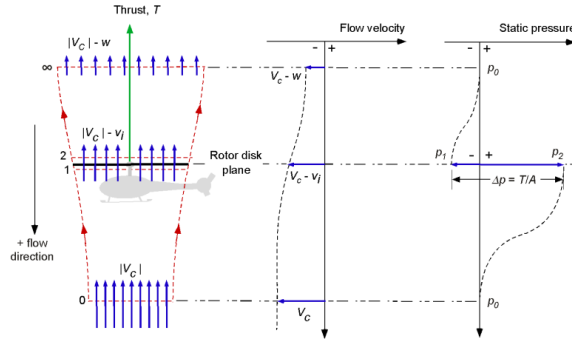


Figure 1.10: Flow model in windmill brake state configuration

©[17]

Region between the hover and the windmill brake state

In this region, as we can't define a control volume, it is impossible to use the momentum theory. Only the experimental data can serve to determine the curves of figures 1.11 and 1.12. An empirical research leads to the following:

$$\frac{v_i}{v_h} = \kappa + k_1 \left(\frac{V_C}{v_h}\right) + k_2 \left(\frac{V_C}{v_h}\right)^2 + k_3 \left(\frac{V_C}{v_h}\right)^3 + k_4 \left(\frac{V_C}{v_h}\right)^4 \quad (1.13)$$

Where $k_1 = -1.125$, $k_2 = -1.372$, $k_3 = -1.718$ and $k_4 = -0.655$.
And with κ the measured induced power factor in hover (usually 1).

For all regimes, one can state that the power ratio is given by:

$$\boxed{\frac{P}{P_h} = \frac{V_C}{v_h} + \frac{v_i}{v_h}} \quad (1.14)$$

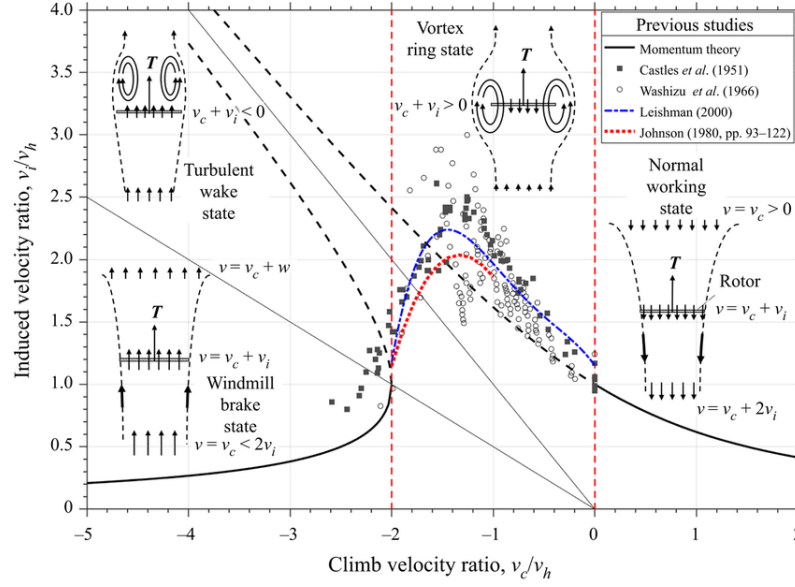


Figure 1.11: Evolution of the induced velocity in function of the climb velocity

©[18]

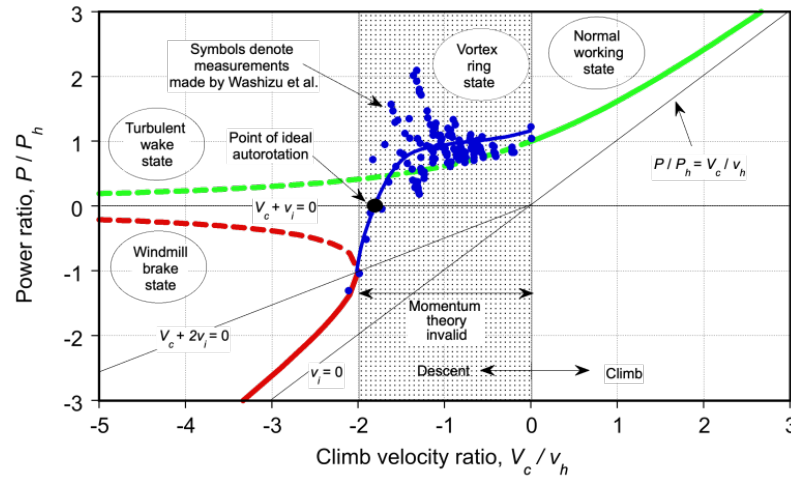


Figure 1.12: Evolution of the power ratio in function of the climb velocity

©[17]

In this region, two kind of instabilities can be encountered, the *Vortex Ring State* and the *Turbulent Wake State*. The first one is reached at relatively high rates of descend, as the rotor descends in the vortices of its own blades. The second one happens at even larger descend rates. The vortices now go above the rotor but it is still an irregular regime.

1.4 Vortex Ring State

The Vortex Ring State - that we will simply call *VRS* in the rest of this document - happens when the descend rate approaches the hover induced velocity. To be more precise, VRS is gonna happen when each blade tip goes into the vortex of the blade before. At that particular moment those vortices merge to form a ring. This Vortex Ring will grow more and more until it reaches the size of the rotor itself, resulting in a huge loss of thrust.

1.4.1 Basics of vorticity

Every flying object generates vortices. These are an immediate cause of how an airfoil produces lift. Under the airfoil, the pressure is higher than the ambient and, in opposition, the pressure is lower above the airfoil. This works fine until we get to the tip of the wing. Indeed, the higher pressure underneath “pushes” the air towards the exterior where the air is at the atmospheric pressure and the lower pressure above “pulls” the same air. The combination of those two effects creates a rotation momentum that results in a vortex. By conservation of momentum, that vortex will remain behind the wing, resulting in a *wake turbulence*[19]³.



Figure 1.13: Visualization of the wake turbulence of an airplane
©Steve Morris

From the *lifting line theory*[21, 22], we define Γ the distribution of circulation and ω the vorticity such that:

$$\omega = \nabla \times \mathbf{u} \implies \Gamma = \int \omega \cdot d\mathbf{S} \quad (1.15)$$

With $\mathbf{S}$ an open surface.

By defining S the wing surface, b the wing span, $\bar{c} = S/b$ the mean chord and $AR = b/\bar{c}$ the aspect ratio such that, for a perfect wing, the lift coefficient C_L and the induced drag coefficient $C_{D,i}$ correspond to the following:

$$C_L = \frac{\Gamma_0 \pi b}{2 U_\infty S} \quad (1.16)$$

$$C_{D,i} = \frac{C_L^2}{\pi AR} \quad (1.17)$$

³The wake turbulences are so strong that the ones generated by a big aircraft suffice to completely return a smaller airplane. For safety reasons, multiples airplanes in final (i.e. just before landing) are thus obliged to maintain a certain distance between them depending from their weight.[20]

We see from equations 1.16 and 1.17 that Γ is proportional to U_∞ and to S while being anti-proportional to b . In the case of a helicopter, S is very small and b is quiet in the norm, letting us expect a small vortex. However, the velocity U_∞ isn't constant at all, it is nil at the axis and maximal at the tip. This leads to the lift curve observable on figure 1.14. The very high U_∞ at the tip is thus responsible for the non-negligible vortex that a helicopter blade will encounter.

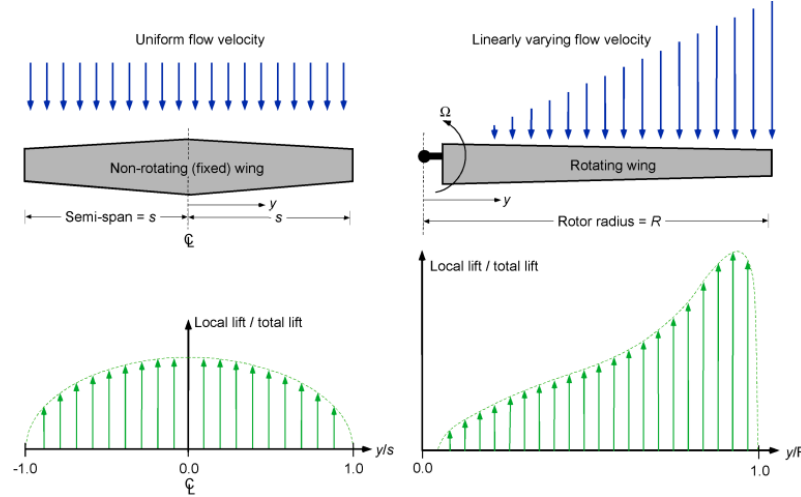


Figure 1.14: Loading of an airplane wing (left) and a helicopter blade (right)

©[17]

1.4.2 Causes of VRS

VRS are generally observed in vertical descend, in a steady air. When the helicopter goes in its own wake, at a proper descend velocity, the vortex of the blade i will be in the path of the blade $i + 1$. The vortices of the two blades will thus merge into a bigger vortex. We can expect all the blades to do the same, leading to a unique, annular vortex: the *Vortex Ring*. If this velocity is maintained, the vortex ring will stay on the rotor, this is the *Vortex Ring State (VRS)*. At that moment, the VRS will grow until it encapsulates the whole rotor. A direct cause of a VRS is the augmentation of the induced velocity. Indeed, since the flow is already driven by the vortex, the rotor will accelerate it even more. This causes the effective angle of attack to be lowered and thus, the thrust to be decreased.

A pilot's reflex at that moment would be to increase the collective pitch to compensate the loss of thrust. This is contra-productive since doing so would reinforce the VRS by increasing even more the velocity of the fluid inside of it.

A visualization of this state is to be found at figure 1.15.

Escape maneuver

To escape a VRS, there are two methods. The classical method consists of inverting the pitch. We oppose the blade to the flow of the VRS and we push it upward. The big disadvantage is the considerable loss in altitude that this maneuver will generate.

The second method is called the *Vuichard recovery*[23]. It consists of pulling the helicopter on the side with the cyclic and the tail rotor to get in the exterior part of the VRS, where the stream is ascending. This method is by far more effective since it results in a lowered loss in altitude. The downside being that a Vuichard is more skill demanding.

The ideal would simply be to avoid entering VRS. To do that, the pilot has to maintain a forward velocity and/or to avoid descending at a too large rate.



Figure 1.15: Demonstration of a VRS using a real helicopter
©AerialStage & Valair

Chapter 2

Simulation tools

The purpose of this chapter is to explain the approach of the problem and to describe the tools that will be used in order to simulate the flight of a helicopter.

2.1 Description of the problem

Airplanes can be considered as perfectly static volumes for the great majority of the simulations that we would want to make about them. This means that one only has to design a fluid mechanics analysis. To simulate helicopters, we do not have this comfort. Indeed, from their most basic principle, helicopters are composed of rapidly moving parts that must be taken in consideration: the blades.

That said, in order to properly simulate a helicopter, we have to use a model able to compute the fluid mechanics on a moving system of multiple bodies.

2.1.1 Approach

At this stage of the problem, we can assume our helicopter to be a set of blades rotating about a virtual axis. We thus completely neglect the cell of the helicopter and, especially, the tail rotor. Considering these would indeed make the post processing even more complicated due to the added interactions. Let's note some important key points about these assumptions:

- All the forces that exist towards the ground (mainly the weight and the drag of the cell) are considered as one single constant and purely vertical force that we will call *total load*.
- Some small vortices may be generated in the hub region, those are non physical but negligible in front of the tip vortices. In addition, an air flux may travel through the hub since it is not implemented. This is also not physical and must be ignored.
- In absence of a tail rotor, the only way to compensate the yawing torque is to virtually force the base of the system to be motionless around the vertical axis. That means that no matter what happens, the blades will turn at the fixed ω speed.

To archive the simulations, we will cut our problem in two parts: the multi-body system dynamics and the fluid mechanics modeling. The multi-body system dynamics (MBS) part has as purpose to simulate all the motions of our system of blades in order to furnish their positions at every time step. The fluid mechanics model, using the *Vortex Particle Method* (VPM) theory, described in section 2.3, will then apply the fluid mechanics equations around three dimensional airfoils placed at those positions.

2.2 Multi-body System Dynamics

The motions of the rotor will be simulated using *Robotran*[24]. This tool has been developed in UCLouvain by the *Multi-body Research Group of the Mechatronics, Electrical Energy and Dynamic Systems (MEED)* team. The idea is to simulate multibody systems through symbolic equations. Robotran is composed of three main parts: MBSysPad, MBSysTran and MBSysC.

MBSysPad is a graphical editor that allows to set our system. We specify the general geometry of the system and the physical properties of all our bodies. In addition, we here indicate all the degrees of freedom that exist between each of our bodies. Once our system is entirely specified, **MBSysTran** will generate the symbolic equations that describe mathematically our system. Then, we can code the behavior of our system through the calculator. In this thesis, we will use **MBSysC** which is coded in C¹. A complete description of robotran is available in the official documentation[25].

2.2.1 Basics of multi-body system dynamics

In a MBS, we link multiple bodies together using joints. Each joint can have one or multiple degree(s) of freedom (DOF). In Robotran, we only define 1 DOF per joint. We thus often have to define several joints in series between two bodies. We will distinguish the *prismatic* joints (T1, T2 and T3) that correspond the translations and the *revolute* joint (R1, R2 and R3) that correspond to the rotations. We thus have a maximum of 6 DOFs corresponding to the 3 translations and the 3 rotations. One must be very cautious while choosing the order of the revolute joints. Indeed, where the translations do not imply any change in our body frame, a revolution does. An important note is that in MBS, all bodies are considered to be perfectly rigid. Only joints allow a motion.

2.2.2 Description of the model

Our model is based on the *Airbus Helicopter H135*[26]. As previously mentioned, we only consider the rotor as we can see on figure 2.1

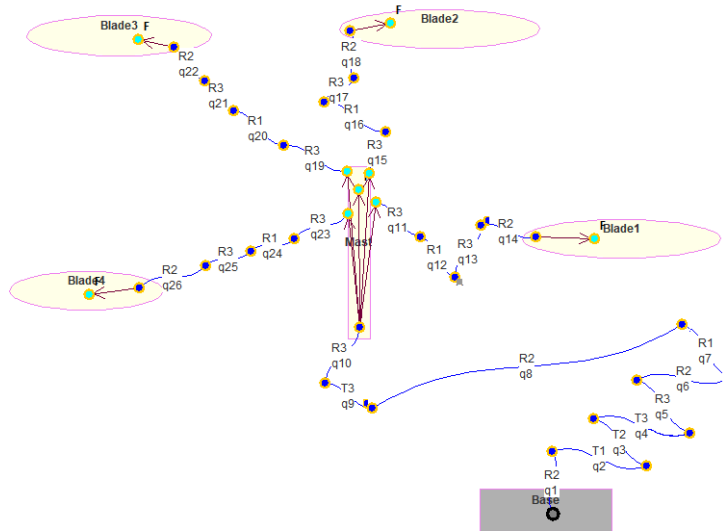


Figure 2.1: Robotran model of the H135

All the joints are described in Appendix A.1

¹Note: two variants, MBSysLab and MBSysPy, respectively in **Matlab** and in **Python**, also exist with the same role. While the **Matlab** and the **Python** environments offer a simpler syntax and don't need to be compiled, C remains the most efficient language of the 3 and is by far the most appropriate for this thesis.

2.3 Vortex Particle Mesh

The traditional way to study fluid mechanics is based on the Eulerian method. We cut our domain into a mesh, then, we compute the solution vector on each node using the values of the neighboring nodes.

In the *Vortex Particle Method (VM)* we compute the solution vector on a set of particles that follows the flow velocity using the Navier-Stokes equations[27].

2.3.1 Basics of vortex particle method

By applying the Navier-Stokes equations on equation 1.15 and by defining a blob ζ to avoid discontinuities, we get:

$$\omega^h(\mathbf{x}, t) = \sum_p \alpha_p^h \zeta_\epsilon(\mathbf{x} - \mathbf{x}_p^h(t)) \quad (2.1)$$

Where the suffix h denotes the approximate value for a particle p ;
 $\alpha_p^h = \mathbf{v}_p \omega_p^h$ is the local circulation;
 And $\zeta_\epsilon = \frac{1}{\epsilon^3} \zeta\left(\frac{\mathbf{x}}{\epsilon}\right)$ a blob of radius ϵ [28].

The primitive models relied entirely on the viscous effects and are completely based on particles. The biggest disadvantage of these purely meshless methods is that, due to the clustering and the spreading of the flow, the particle distribution may be distorted. Such kind of distortions lead to unwanted inaccuracies. In order to limit those inaccuracies, one introduces the *Hybrid Vortex Method*[28].

Hybrid Vortex method

The idea of the hybrid method is to reintroduce the use of a mesh. In order to achieve that, one has to create a translation from the flow field to the mesh grid (and vice-versa) such that:

$$\mathbf{a}_k = \frac{1}{\mathbf{V}_k} \sum_p \nu_p \mathbf{a}_p \phi_k(\mathbf{x}_p) \quad \mathbf{a}_p = \sum_k \mathbf{a}_k \phi_k(\mathbf{x}_p) \quad (2.2)$$

Where the suffix p stands for the particle point of view and k the mesh point of view;
 $\mathbf{a}$ is the flow field and $\mathbf{V}_k$ is the volume around $\mathbf{x}_k$.

The basis function ϕ_k is defined as follows in order to respect $\sum_k \phi_k = 1$:

$$\phi_k(\mathbf{x}_k) = \phi\left(\frac{\mathbf{x}_p - \mathbf{x}_k}{h}\right) \quad (2.3)$$

Where h is the mesh size (for a uniform mesh).

Vortex Particle Mesh Method

One of the most common hybrid method is called the *Vortex-In-Cell (VIC)* or *Vortex Particle Mesh Method (VPM)*. The main advantages of the VPM are among others: the easiness of implementation, the coupling possibilities, the low diffusive effects, et cetera. A recent and efficient method is the *Large-Eddy Simulation (LES)* that respects[29, 30]:

$$\frac{D\omega}{Dt} = (\omega \cdot \nabla)\mathbf{u} + \nu \nabla^2 \omega + \nabla \cdot \mathbf{T}^M \quad (2.4)$$

With ν the kinematic viscosity and $\mathbf{T}^M$ the sub-grid scale model.

2.3.2 Description of the model

For this thesis, we will use *VPM4x*, a tool developed by the *Thermodynamics and FLuid mechanics (TFL)* team of UCLouvain. *VPM4x* uses the VPM theory with 3D LES. For efficiency reasons, *VPM4x* is coded in the low level language **Fortran**. Let's note that a particularly interesting option available in *VPM4x* is the ability to move the computation boundaries during the computation.

Our model can be described as follows: the hub position is fixed thanks to *Robotran* in the center of our calculation box with the rotation axis placed on the z axis. The x and y boundaries are free to move and the z boundaries are the ones through which the flow goes in and out. For convenience, in the rest of this thesis, the z boundary placed above the rotor will be called the *inflow* and the z boundary placed under the rotor will be called the *outflow* even if the flow is reversed (in which case, the inflow will be said to be negative).

On each of the blades, we assign a *NACA 0012* airfoil profile with respect to the positional information provided by *Robotran*.

2.4 Computing

The *Robtran/VPM4X* coupling is designed to run on massively parallel computers. The computations will be performed on the *CÉCI* clusters[31] and more particularly on *NIC5*[32]. This cluster is hosted in ULiège and has 73 nodes of 2 AMD Epyc Rome 7542 CPUs and 256 Go of RAM. Each of those CPU has 32 cores clocked at 2.9 GHz.²

The computations done, all the post processing is made on a personal computer with **Python** and **Paraview**.

²Note: each user is allowed to use a maximum of 5 nodes (320 cores) at a time for 48h straight.

Chapter 3

Hovering

The very first part of this thesis is the validation of the model. To do so, one must firstly be able to maintain the rotor in a stationary state and to observe its behavior.

3.1 Base model

Our model is a set of four 4.75 [m] long blades rotating around a hub of diameter 0.7 [m]. The total rotor diameter D is thus 10.2 [m] and the total load is fixed to 29.412 [kN]. The calculations are held in a computation box of $2D \times 2D \times 6D$ with the rotor fixed in the center ($3D$ above and $3D$ under the rotor). For the hover, we will mesh our grid with 64 elements per diameter (i.e. $128 \times 128 \times 384$ elements) and the computation is held with 256 cores distributed among the dimensions as $4 \times 4 \times 16$.

3.1.1 Theoretic expectations

Using equation 1.7, we find that with:

$$T = 29\,412 \text{ [N]} \quad (3.1)$$

$$\rho = 1.2 \text{ [kg m}^{-3}\text{]} \quad (3.2)$$

$$A = 5.1^2 \cdot \pi = 81.71 \text{ [m}^2\text{]} \quad (3.3)$$

$$(3.4)$$

We have:

$$v_h = 12.25 \text{ [m/s]} \quad (3.5)$$

And equation 1.8 gives:

$$P_h = 360\,297 \text{ [W]} \quad (3.6)$$

In addition, we know that, in hover, we should have $U_\infty = 0$. But since our calculation box is finite, and quite close from the rotor, we expect to measure a non-zero velocity at the box inlet while hovering. To align our results with the theory, we will measure this velocity as an error ϵ_C that we will assume constant¹ across all the regimes that we will go through in descend flight.

¹One will note that this assumption is probably wrong, but to verify it, one should use a calculation box big enough to observe a zero inflow-velocity in hover and measure the velocities slightly above the rotor in different regimes to make comparisons. If such a box was in his budget, one should simply use it since the results would be more accurate.

3.1.2 Observation

Firstly, we will use a free inlet with a controller that will continuously vary the pitch until the thrust converges to the target value of 29.412 [kN]. That done, the simulation will be held again with a fixed pitch, imposed at a value corresponding to the average of the converged controlled pitch.

Controlled pitch

On the figure below, we can observe how the thrust evolves on a 60s simulation. The light blue curves represent the direct measured thrust while the blue curves are rolling averages of 100 data ($\sim 0.13s$). The mean thrust is 29.444 [kN] in the last 10s, which is a very acceptable error.

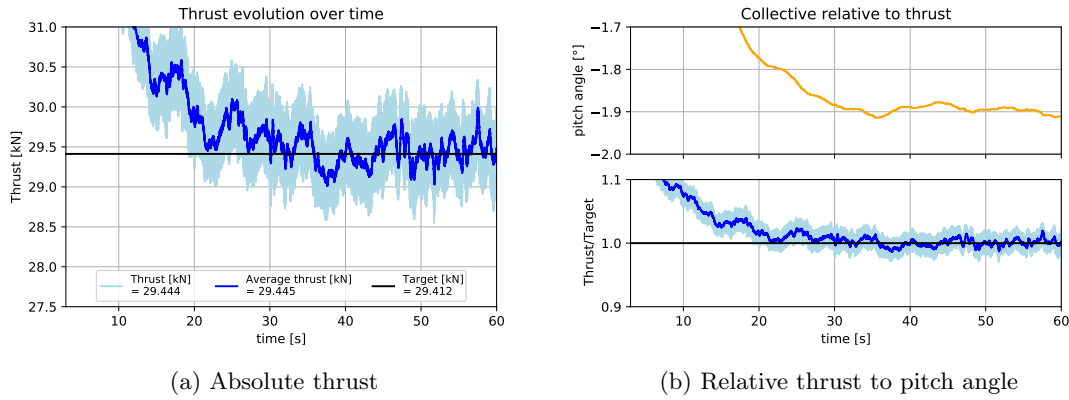


Figure 3.1: Thrust evolution in controlled pitch trimming

We see that the pitch converges towards $-1.9 [^\circ]$.

Fixed pitch

We will here validate our pitch value by re-running free inlet simulations while forcing it. The best result was obtained at $-1.9 [^\circ]$ (exactly -0.033139 [rad]).

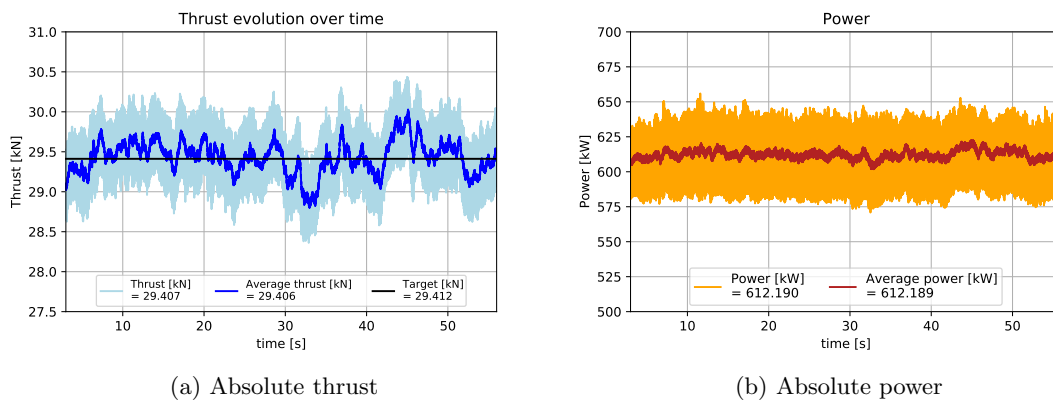


Figure 3.2: Thrust and power evolution in fixed pitch hover

This time, we observe a mean thrust 29.407 [kN] on the last 30s. This is extremely close from the target value. We can thus validate this pitch value. On the right graph, we observe a mean power of 612.19[kW]. This is almost the take-off power that the transmission allows (i.e. 616[kW][26]). The wake of this regime is to be seen on the figure 3.3. This wake matches the theoretical one (figure 1.8), validating our hover configuration.

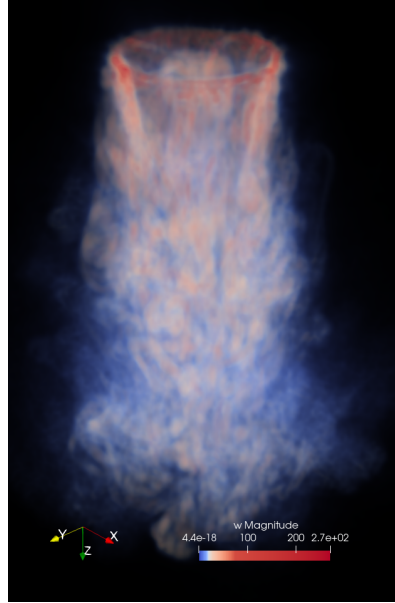


Figure 3.3: Wake in fixed pitch hover (instantaneous at 42.5s)

3.1.3 Mod4 integration problems

We can see on figure 3.2 that, even being in a stable regime, the resulting data are very unsteady. This is unexpected and is problematic since we want to go through an extremely unstable regime: the VRS. This unsteadiness would result in unusable data in such regime. The designated guilty phenomenon would be *the mod4 integration error*. Indeed, equation 2.4 is computed on a mesh composed of cubes in which our blades are rotating. Sometimes, a blade is aligned with the mesh, the rest of the time, it isn't. The integration differences between an aligned and a non-aligned blade produce an error. Since our helicopter has 4 blades, at some time steps, all the blades are aligned with the mesh, and at the others time steps, none of them are. The error of the misalignment would thus be the same for all the blades at every time, amplifying the global error.

To avoid that problem, one has 2 solutions. The first one is to use a way more refined mesh (i.e. reducing h in equation 2.3), reducing the error to a point it becomes negligible. The problem of this solution is that it would greatly increase the cost of a simulation, which is not possible for this thesis. The second solution is to change the number of blades to an odd number, doing so, two blades would never be aligned at the same time, reducing the global error.

3.2 3 blades model

It is chosen to remove one blade from our model to avoid the *mod4 integration error*.

3.2.1 Description of the new model

Our new model, presented in appendix A.1 (figure A.2), has thus 3 blades spaced by 120° . The total load is halved to 14.706 [kN]. Doing this will also reduce the load on each blade, limiting the error even more. To reduce the computation time, the simulations will be held in a box of dimensions $2D \times 2D \times 5D$ ($2D$ above and $3D$ under the rotor), always at 64 elements per diameter ($128 \times 128 \times 320$ elements). It permits a distribution of $4 \times 4 \times 20$ cores (320 cores).

Let's note that the new model is closer to the *Airbus H125*[33] (previously Eurocopter AS350) which is a single-engine helicopter with an empty weight of 1241[kg] and a MTOW² of 2800[kg] (the empty weight of the *H135* is 1460[kg] and its MTOW is 2900[kg]) and has a take-off power of 632[kW][34] (appendix A.2).

3.2.2 Theoretic expectations

With a reduced load, we should also observe a smaller hover induced velocity. As previously:

$$v_h = 8.66 \text{ [m/s]} \quad (3.7)$$

$$P_h = 124\,756 \text{ [W]} \quad (3.8)$$

Ignoring the hub and using the annulus of the blade instead of the complete disk gives:

$$v_h = 8.68 \text{ [m/s]} \quad (3.9)$$

$$P_h = 125\,044 \text{ [W]} \quad (3.10)$$

3.2.3 Observation

Since we changed our configuration, we must re-trim our model using a similar procedure as before.

Controlled pitch

On the figure hereunder, we see the evolution of the thrust over time with the controller.

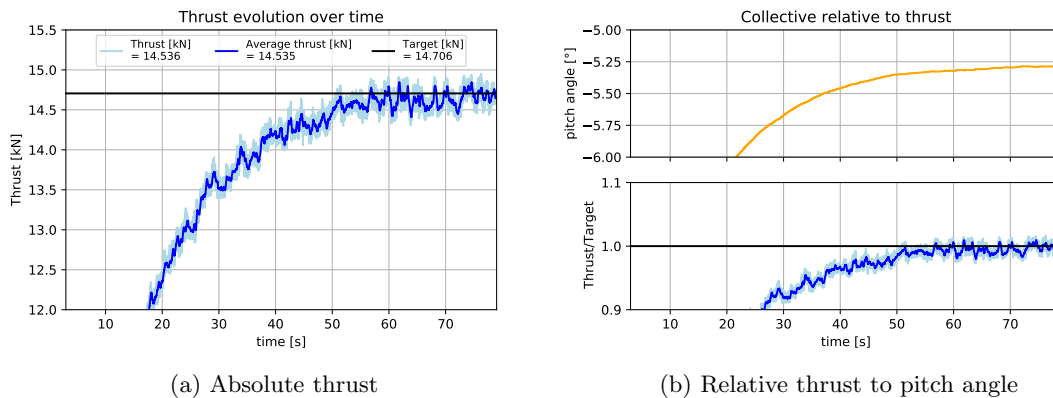


Figure 3.4: Thrust evolution in controlled pitch trimming

We observe a convergence of the pitch towards -5.3° . But, due to the slowness of the controller, this value is only observed at the very end of the simulation, an intermediate simulation is run to confirm the pitch.

²Maximal Take-Off Weight

Semi-controlled pitch

This simulation uses a fixed pitch during 10s at approximately -5.3° (exactly -0.092 [rad]), then it is controlled again for the rest of the simulation. This is illustrated on figure 3.5. It convinces that the pitch is converged (the scale of figure 3.5b is at a ridiculous range of 0.03° which is practically immeasurable).

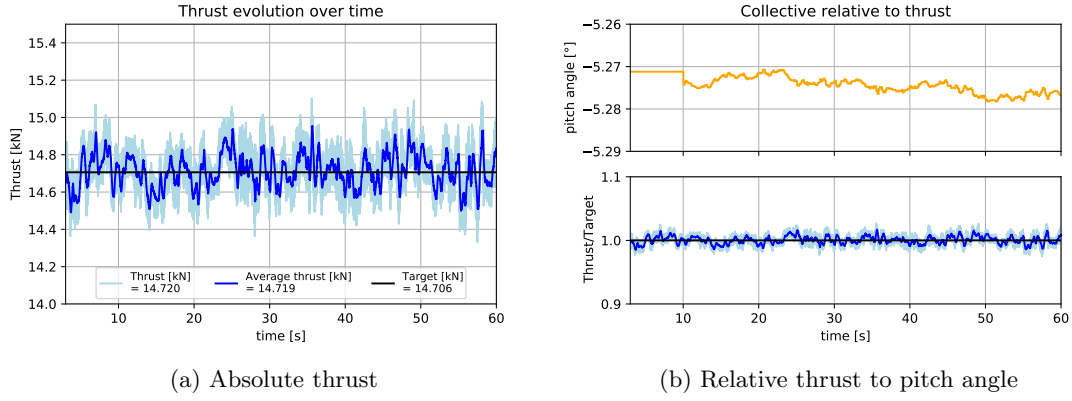


Figure 3.5: Thrust evolution in semi-controlled pitch trimming

3.2.4 Comparison between both models

By comparing the non-dimensional graphs with the same y-axis for the 2 configurations (figure 3.6), it appears clearly that the new model is way more stable, indeed, the light blue curve, representing the real measured data is clearly less unsteady. The average curve also shows a slightly more stable tendency, with smaller peaks and a general tendency to oscillate closer to the target. This is steady enough to expect acceptable data in the VRS region.

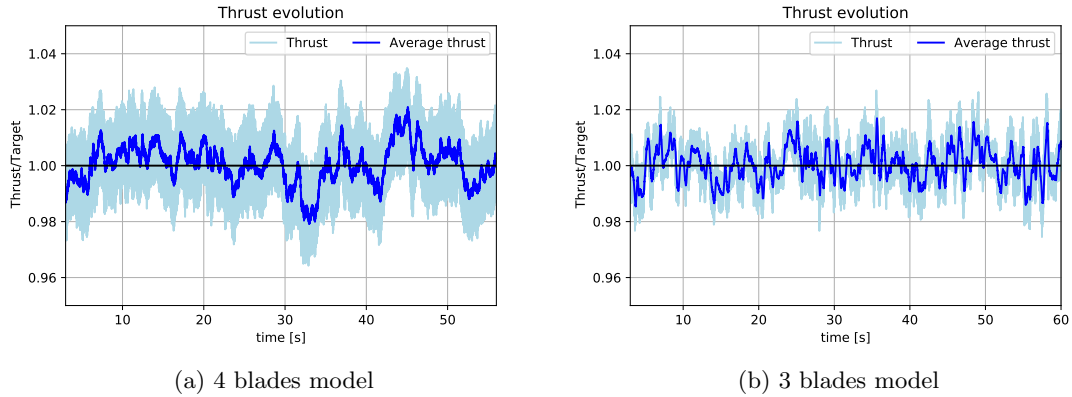


Figure 3.6: Relative thrust evolution comparison

3.2.5 Defining the hover condition

Before going to descend flight, one must define the hover condition as a reference. The following simulations are ran on the descend configuration explained in section 4.1. We must here define our hover values definitively.

Fixed pitch, free inlet

After re-running a controlled pitch simulation, we obtain $\theta_h = -0.089 [\text{rad}] \simeq -5.1 [^\circ]$ ³. In this simulation, we will measure the mean velocity of the inlet of the calculation box at $1.15 [\text{m s}^{-1}]$. We also directly see that the induced speed (V_{mean}) is in the right order of magnitude.

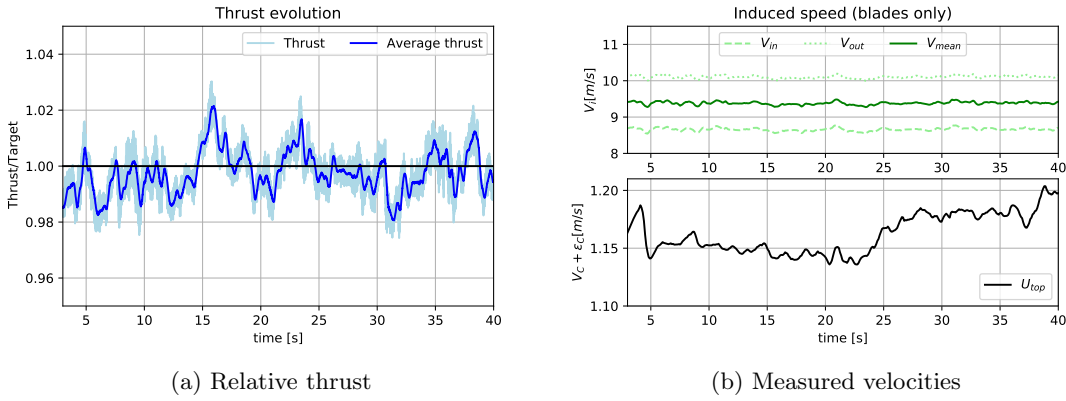


Figure 3.7: Thrust and velocity evolution in fixed pitch hover

Fixed pitch, forced inlet

This simulation (figure 3.8) will be our reference for the dimensionless parameters, we will force the inlet velocity and measure all the hover values as an average over the whole simulation. We see here an acceptable difference of thrust with the target value. The measured induced velocity and the measured power are a bit higher than the theoretical ones. This can be explained by the non-uniformity of the velocity distribution and the negligence of the drag force. Anyway, the differences are small enough to validate our hovering model.

³It has changed a little bit for non-physical reasons linked with the reuse of a bigger computation box.

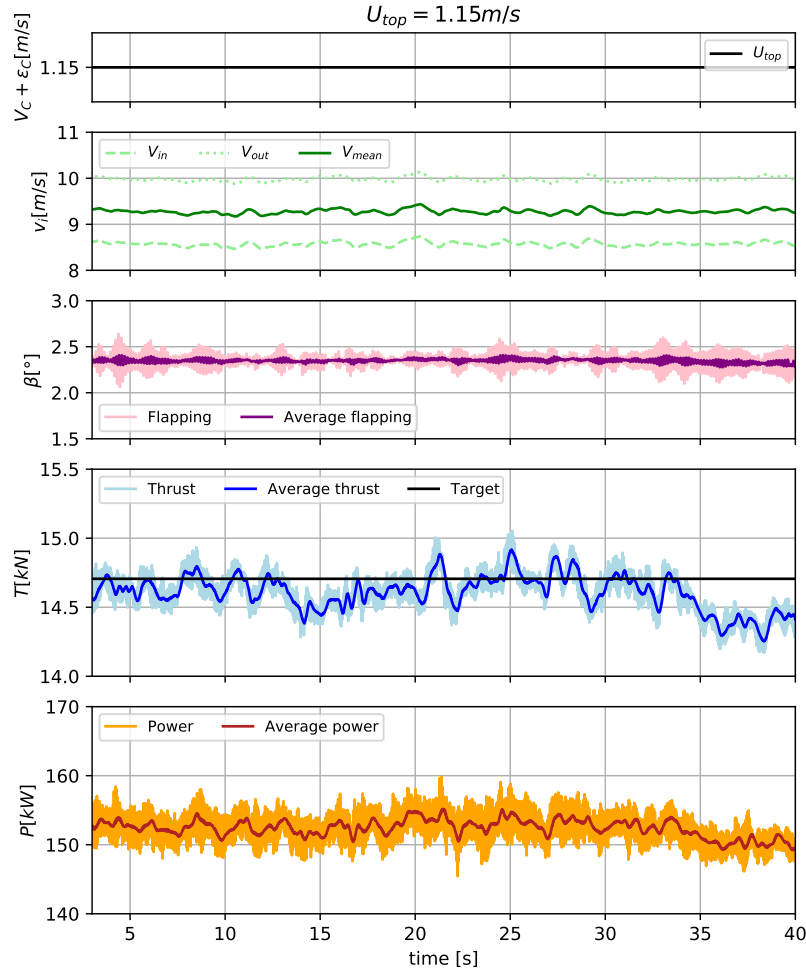


Figure 3.8: Reference hover

We can now state that our hover values are:

$$\theta = -0.089 \text{ [rad]} \simeq -5.1 \text{ [}^\circ\text{]} \quad (3.11)$$

$$U_{top,h} = \epsilon_C = 1.15 \text{ [m s}^{-1}\text{]} \quad (3.12)$$

$$v_{i,h} = 9.273 \text{ [m s}^{-1}\text{]} \quad (3.13)$$

$$\beta_h = 2.35 \text{ [}^\circ\text{]} \quad (3.14)$$

$$T_h = 14.636 \text{ [kN]} \quad (3.15)$$

$$P_h = 152.305 \text{ [kW]} \quad (3.16)$$

The temporal average in the xz - and the yz -plane gives us respectively the streamlines with the velocity-magnitude field (figure 3.9a) and the vorticity magnitude field (figure 3.9b)⁴. We can also have a look to the 3D wake (figure 3.10) to see that we are following the theoretical trumpet shape (figure 1.8).

⁴Note: the 0.4 exponent of this figure is used to re-scale the data in order to make them more readable, it has no physical meaning.

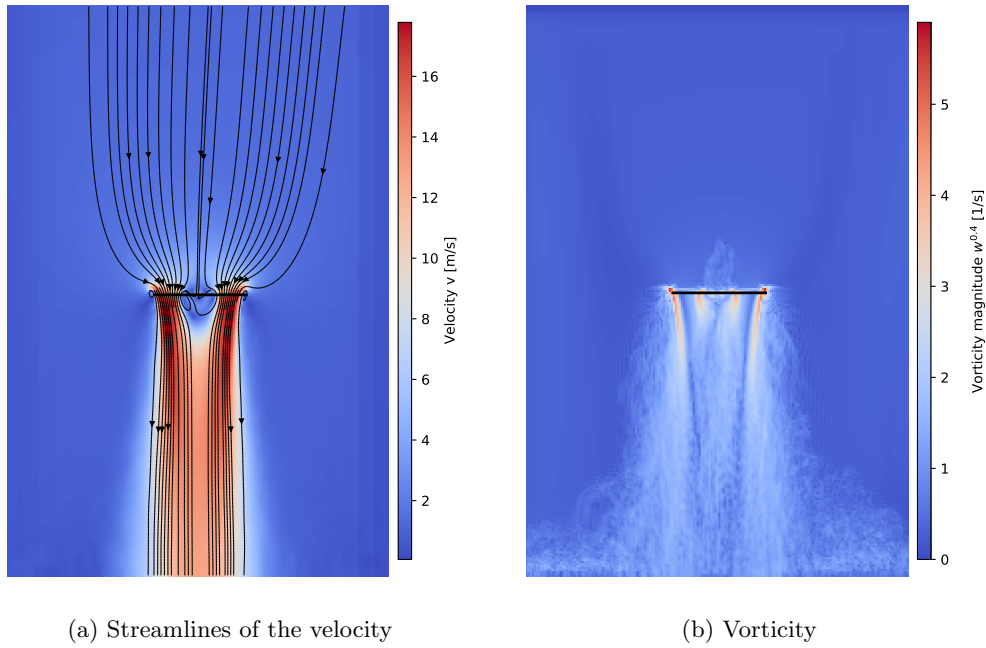


Figure 3.9: Time-average field of the xz - and the yz -planes combined
 $[1s - 40s]$, 10 measures/s (780 data)

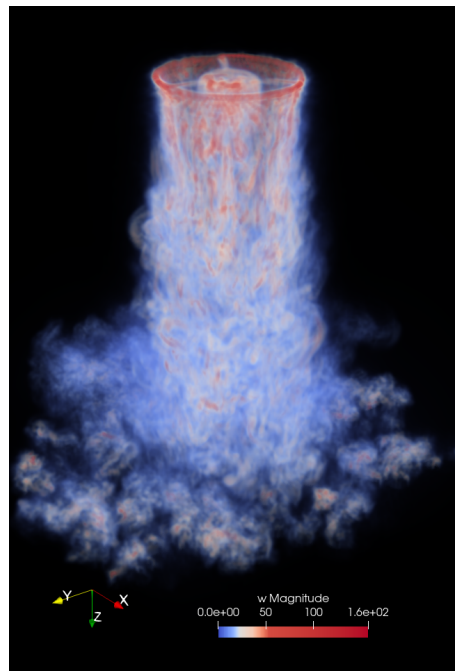


Figure 3.10: 3D wake in reference hover (instantaneous at 20s)

Chapter 4

Descending flight

4.1 Methodology

In order to simulate a helicopter in an axial descend, one has 2 ways to go. The first one, also the ideal one, is to use a very long computation box and to force the helicopter to move inside of it. This method permits an easy way to control our descend velocity and is the closest from reality. The problem of this method lies in the huge calculation cost of this box. For this thesis, doing so would permit us to only make simulations of a few seconds, which is too few to properly analyze the data. We will thus use the second method: simulating a wind tunnel by forcing an inflow at the top of the box. Doing so allows to keep a small box while observing the phenomena for quiet a long time. The disadvantages of this method is that we are very limited by *VPM4x* concerning this inflow velocity and the system will not be able to react any kind of phenomenon.

4.1.1 Setup

We will use a calculation box of $2D \times 2D \times 6D$ with 48¹ elements per diameter ($96 \times 96 \times 288$ elements) distributed on $4 \times 4 \times 18$ cores (288 cores in total). The rotor is placed in the very center of this box as illustrated on figure 4.1. The upper boundary will be called “inflow”, this will be our controlled boundary. The bottom boundary or “outflow” is a free boundary. The reader will note that the inflow can be set to a negative value, in this case, air will enter the box through the outflow and exit from the inflow. I permit myself this abuse of language for better convenience. As a reminder, the lateral boundaries are free to move dynamically to adjust themselves to the vorticities, $2D \times 2D$ are thus initial values.

In order to measure the induced velocity, two measurement slices are placed above and under the rotor. In post-production, only the annulus² corresponding to the blades will be kept to obtain an averaged value for v_i . Those slices must be as close as possible from the rotor plane without intersecting it. Since, due the flapping angle β , the blades form a cone, the bottom slice can be the rotor plane itself. But on the other hand, the upper slice must be placed higher. One element measure 0.2125[m] and the vertical position of the blade tips is about 0.2[m] in hover. Placing the slice here would not permit the flapping angle to increase - and it will - thus the upper slice is placed two elements above the rotor plane.

¹The number of elements has been reduced to 48 instead of 64 to limit the cost, permitting ~ 2 times faster simulations.

²The theory uses a disk for this measurement, using the assumption of a uniform flow. But since the hub isn't modeled here, air can go through it in either one or the other direction, adding a non-physical error the the measurements. To avoid this problem, we will simply ignore the hub region to perform the averaging.

We have:

$$W_{x,0} = W_{y,0} = 2D \quad (4.1)$$

$$H_z = 6D \quad (4.2)$$

$$D = 10.2[\text{m}] \quad (4.3)$$

$$D_h = 0.7[\text{m}] \quad (4.4)$$

$$h_i = 0.425[\text{m}] \quad (4.5)$$

$$h_o = 0[\text{m}] \quad (4.6)$$

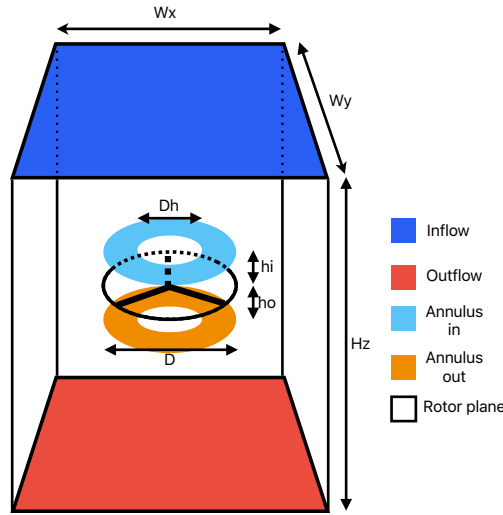


Figure 4.1: Synthetic representation of the simulation box

4.1.2 Approach

In order to obtain valid results, one must begin each simulation with a well known initial condition: the hover. Then one must progressively change the inflow until he gets to the desired descend rate. To control the inflow velocity, *VP4x* permits to use a “ramp”: we choose an initial velocity, a final velocity and two time steps between which the velocity will change linearly. But we can only do it once for each simulation, meaning that if we want to use multiple ramps, we must manually restart the simulation for each ramp. We now have to face a choice: choosing a steep ramp reduces the computation cost but could hide some phenomena; choosing a slight ramp helps to observe efficiently everything but is more costly. I have tested two approaches:

- Single ramp: going immediately from the hover to the desired descend rate.
- Double ramp: going from hover to a stable descend point, then use this point as a new initial condition and going to the final descend rate with a slight ramp.

Those two approaches are represented on figure 4.2. After testing both approaches, it seems that the VRS initiation is a very fast event (see chapter 5) and that the slight ramp doesn’t offer more information. We will thus only use a single ramp configuration since it is less costly.

In addition to the analysis of VRS, we will try to redo the graph of figures 1.11 and 1.12. Starting from the hover, we will thus simulate ramps to 0, -2, -4, -6, ... [m s^{-1}] until the windmill state is reached. This is shown on figure 4.3. The reader will note that the 3 first simulations are shorter, they indeed converge really quickly and don’t need to be longer. Please note that the pitch θ will remain constant for all those simulations.

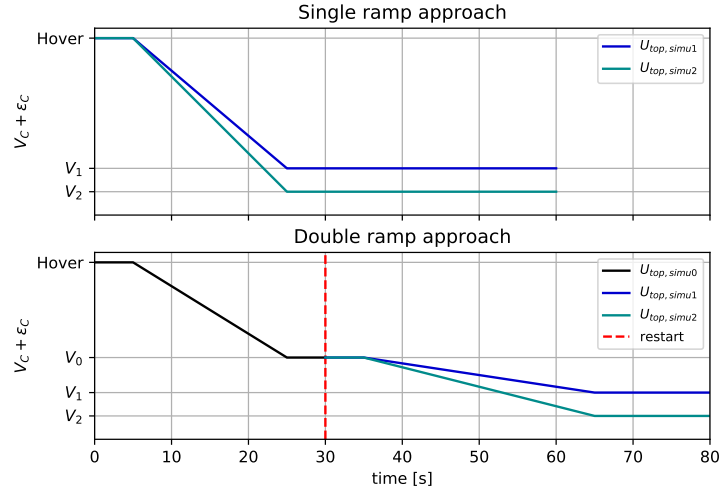


Figure 4.2: Different approaches comparison

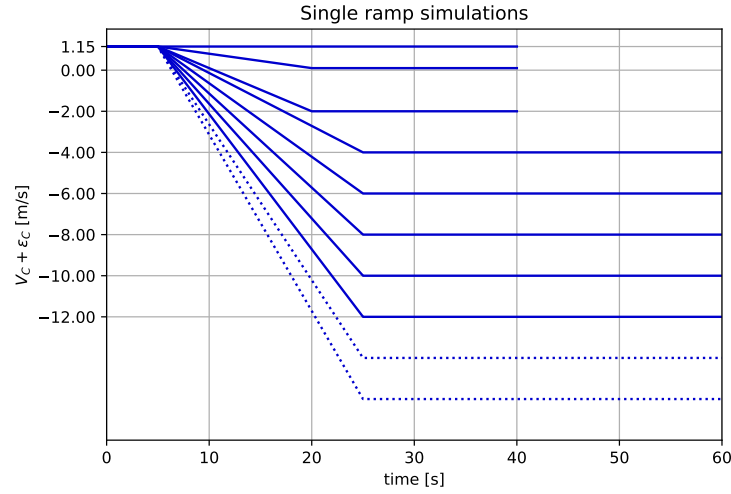


Figure 4.3: Descend flight simulations

The next sections are about the 4 regions of descend flight: the “stable” region³, the vortex ring state region, the turbulent wake state region and the windmill brake state region. The interested reader will find the 3D wakes for every regime in appendix B.1.

³I have split the VRS region in 2 since in very slow descend, we do not observe any VRS behavior.

4.2 Stable region

The so-called “stable” region is the region where the descend is slow enough to avoid the rotor to reach its own wake. In this regime, a pilot can perfectly control his machine⁴. At the limit of this regime with the VRS, some instabilities are expected to occur since we will be near our wake which is - per definition - turbulent. Hereunder is a reminder of the expected streamlines. Please note that this particular plot is only valid in hover or in ascending flight. Indeed, the streamlines shouldn't be coming from above in descend flight.

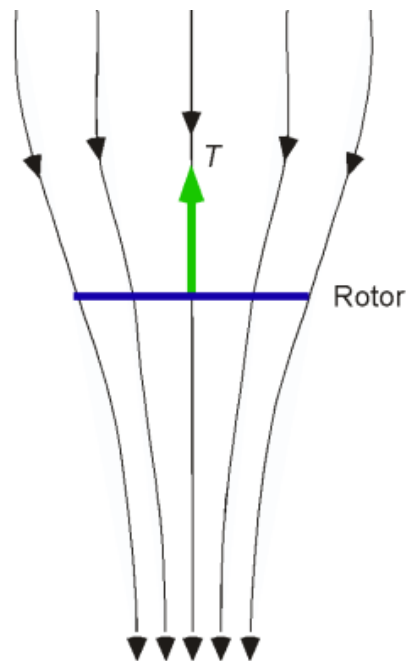


Figure 4.4: Theoretic streamlines expectation

©[17]

⁴In normal operations, a pilot should always stay in this regime, were he can safely stop his descend at every moment.

4.2.1 $V_C + \epsilon_C = -0.1 \text{ m/s}$

The simulation at $-0.1 \text{ [m s}^{-1}]$ ⁵ doesn't show any particular behavior in comparison with the hover except the streamlines, (figure 4.6a) which are no more in trumpet shape, and the induced velocity that has increased.

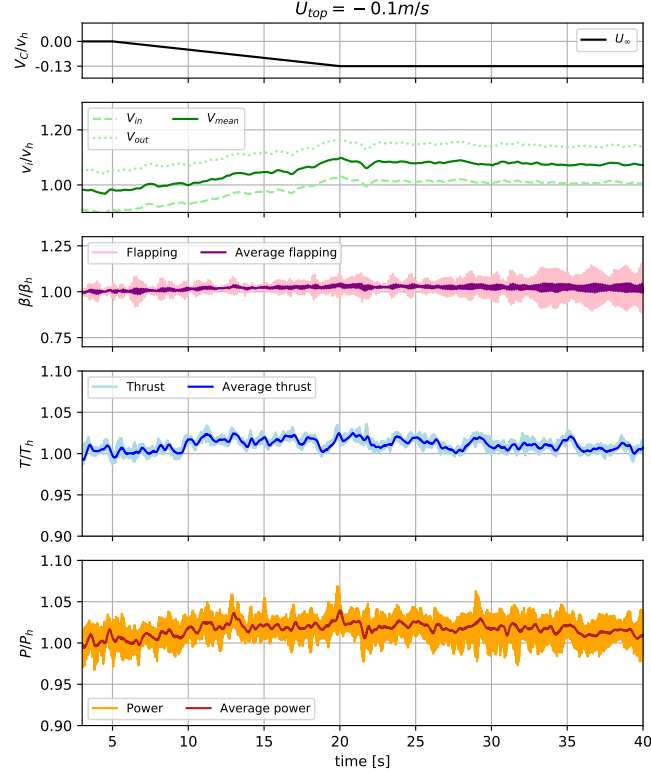


Figure 4.5: Descent at $V_C + \epsilon_C = -0.1 \text{ [m s}^{-1}]$

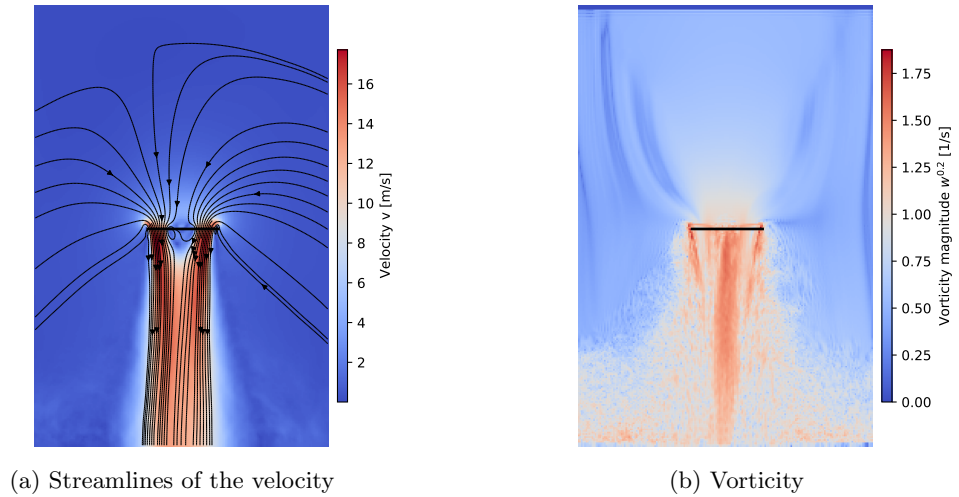


Figure 4.6: Time-average field of the xz - and the yz -planes combined [20s – 40s], 10 measures/s (400 data)

⁵This simulation isn't held at 0 m/s since, for some reason, *VPM4x* doesn't allow it. The reader will note that, in this case the inflow is basically a wall.

4.2.2 $V_C + \epsilon_C = -2m/s$

In this simulation, the streamlines show a real descend behavior. In addition to the induced velocity which has increased again, we see that the thrust and the power are increasing. This shows that, in reality, the helicopter would be slowing down. It proves that the pilot has full control in this regime. The flapping also begin to rise as a consequence of this braking behavior.

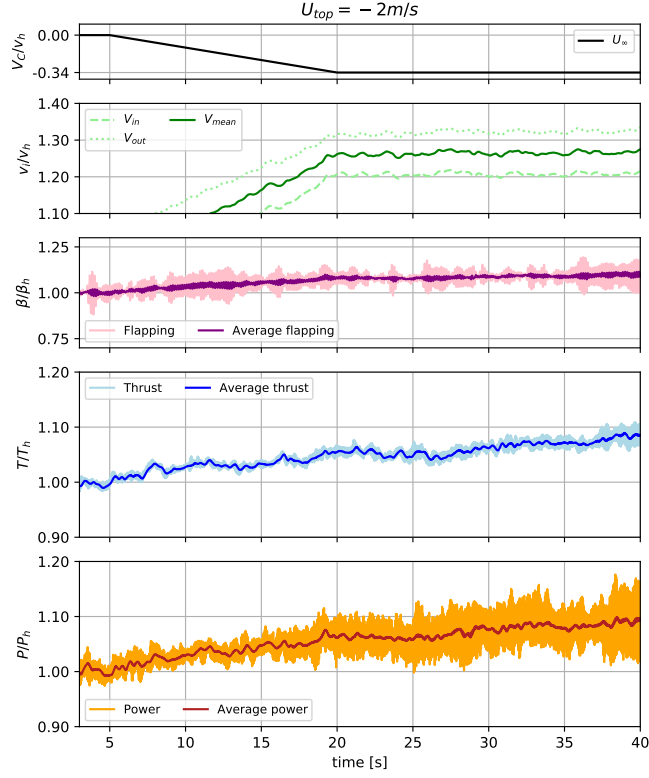


Figure 4.7: Descend at $V_C + \epsilon_C = -2 [\text{m s}^{-1}]$

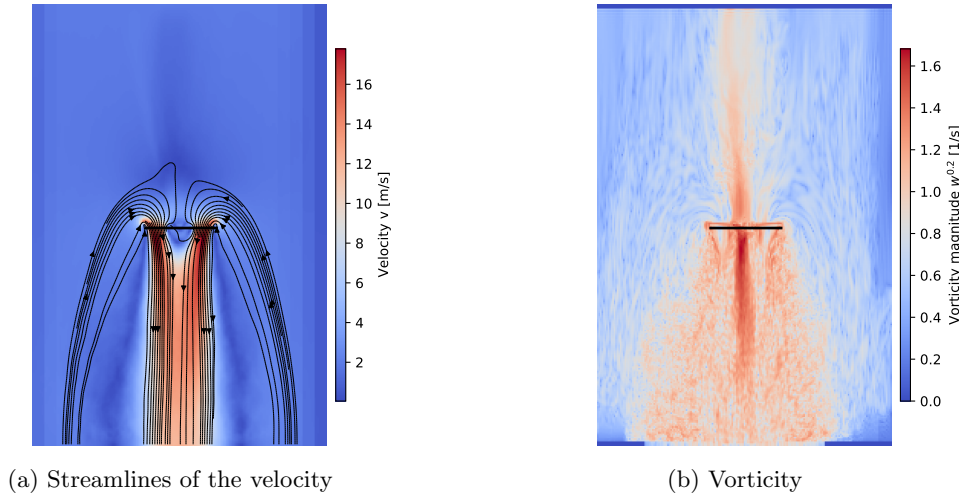


Figure 4.8: Time-average field of the xz - and the yz -planes combined $[20s - 40s]$, 10 measures/s (400 data)

4.2.3 $V_C + \epsilon_C = -4m/s$

From now, things begin to be a bit more interesting. We can tell that the helicopter begins to be shaken since the thrust and the power are becoming unsteady. The pink curve of the flapping shows “bulbs” that are the result of noticeable vibrations on the blades. A look at the streamlines shows that we start to observe some recirculations below the rotor plane, cause of those vibrations.⁶

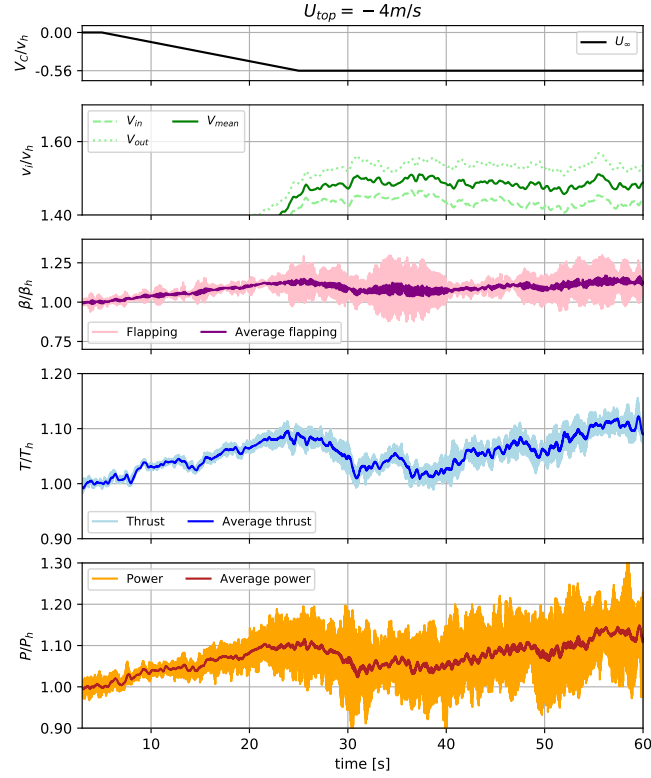


Figure 4.9: Descend at $V_C + \epsilon_C = -4 [\text{m s}^{-1}]$

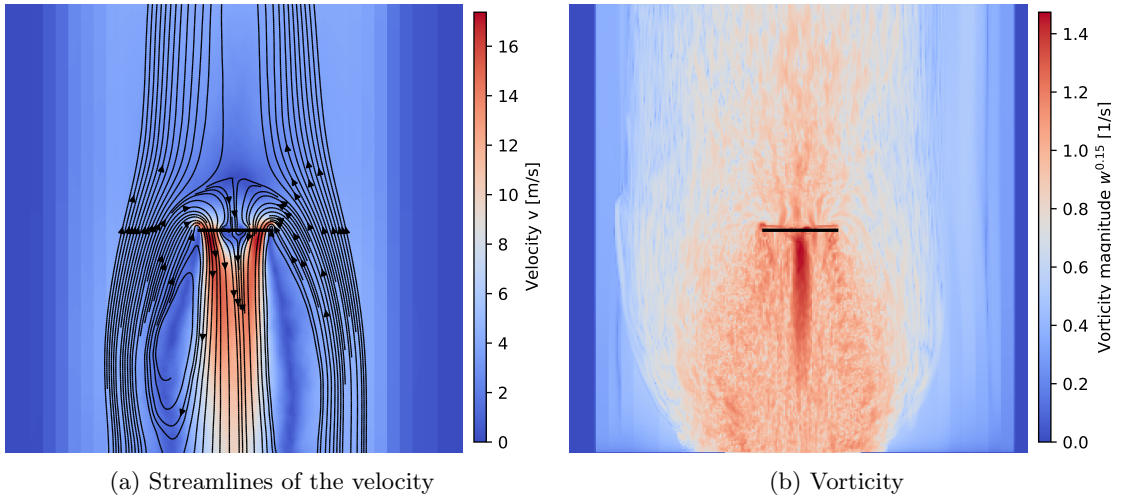


Figure 4.10: Time-average field of the xz - and the yz -planes combined [30s – 60s], 10 measures/s (600 data)

⁶Note: the kind of lines on the side of figure 4.10a and 4.10b are a direct consequence of the moving boundaries of the computation box, it has no physical meaning and should be ignored.

4.2.4 $V_C + \epsilon_C = -6\text{m/s}$

There are now evident recirculations below the rotor. The previous observation still hold: we notice important vibrations. While not being dangerous for the passengers, this regime shows an evident lack of comfort. The power also begins to be particularly unsteady (orange curve on figure 4.11), varying by about 20%. It is certainly not good for the structure of the helicopter and especially for the engine(s).

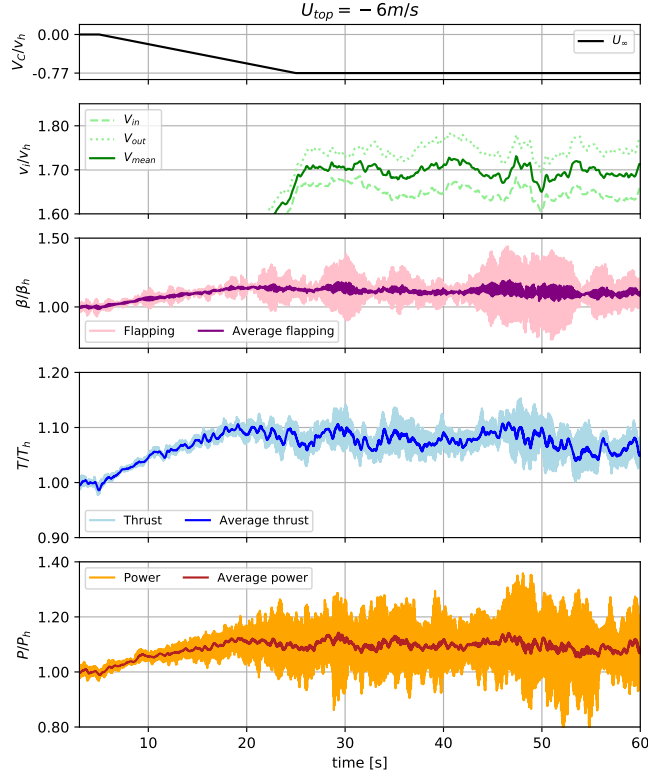
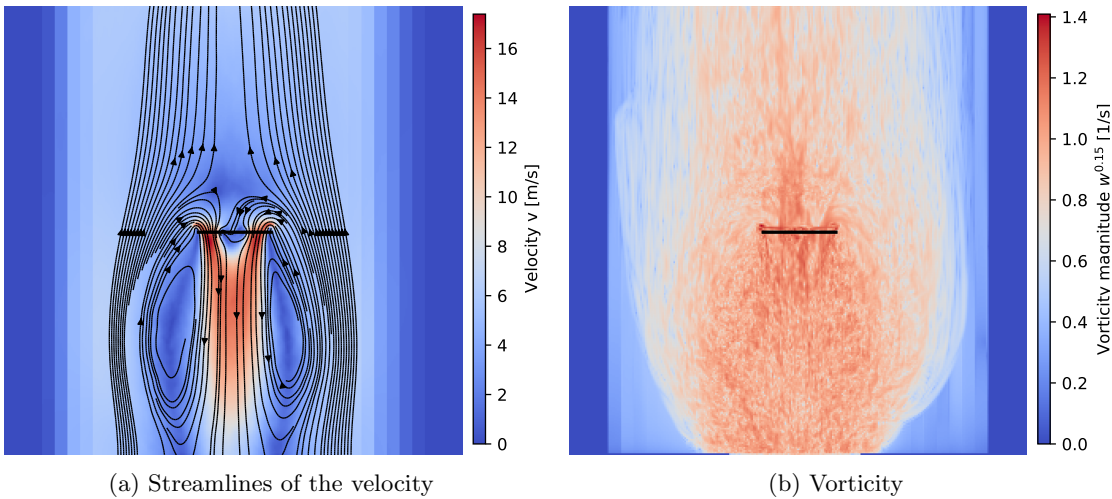


Figure 4.11: Descend at $V_C + \epsilon_C = -6 [\text{m s}^{-1}]$



(a) Streamlines of the velocity

(b) Vorticity

Figure 4.12: Time-average field of the xz - and the yz -planes combined $[30\text{s} - 60\text{s}]$, 10 measures/s (600 data))

4.2.5 $V_C + \epsilon_C = -8\text{m/s}$

We are now at the frontier with VRS, the recirculations lie just below the rotor. At some moment, a vortex ring is created, explaining the “peaks” in the thrust curve ($t= 35, 45, 95, 115$ and 130 s on the blue curve of figure 4.13). This regime is particularly unsteady, too slow to really enter the VRS zone but fast enough to initiate it.

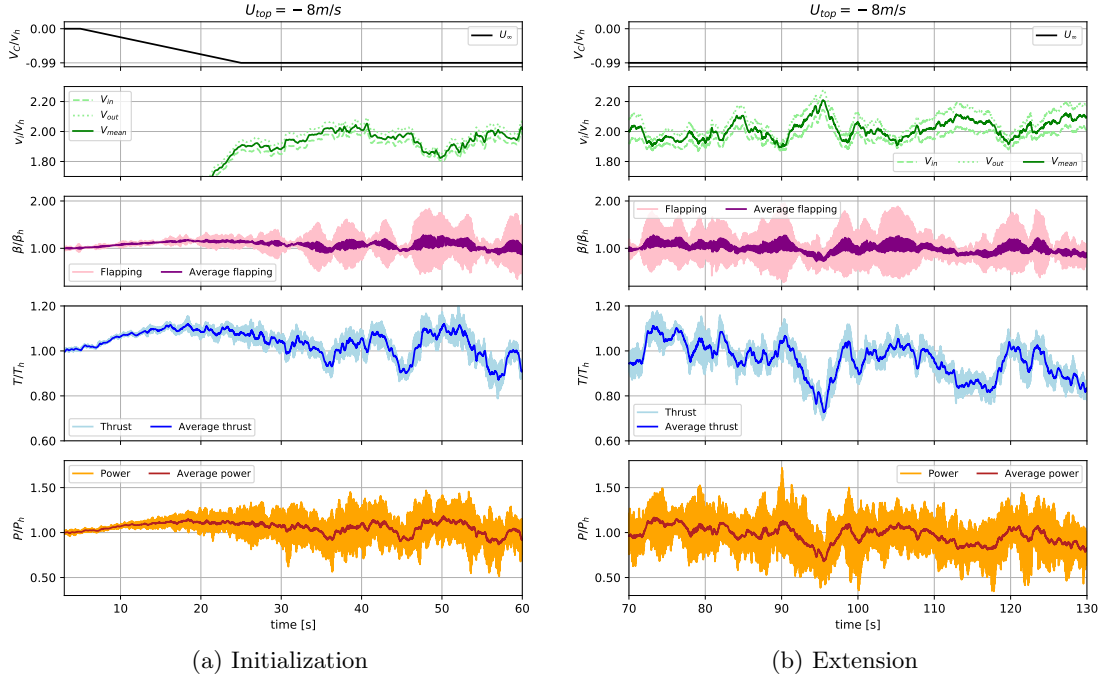


Figure 4.13: Descend at $V_C + \epsilon_C = -8\text{ [m s}^{-1}\text{]}$

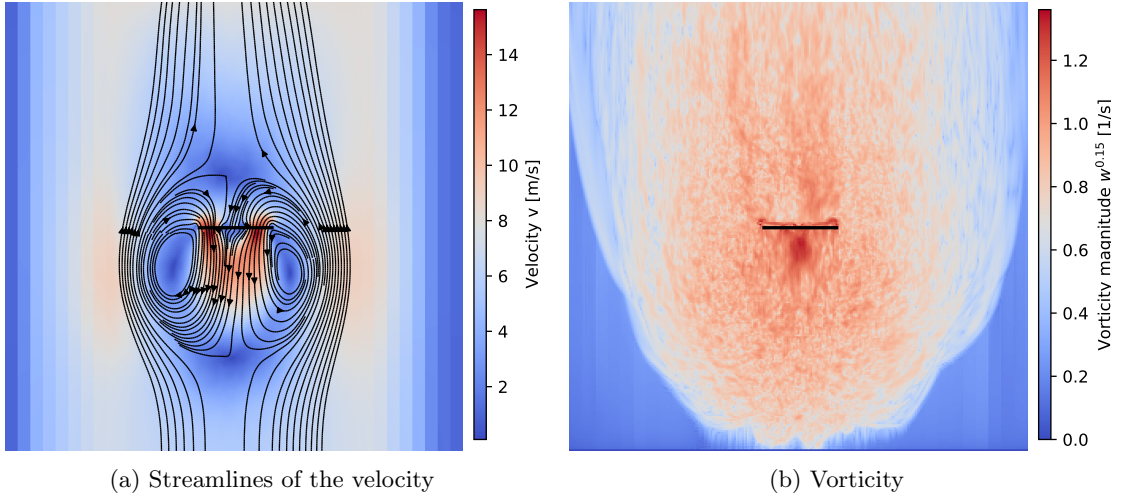


Figure 4.14: Time-average field of the xz - and the yz -planes combined
[70s – 130s], 40 measures/s (4800 data)

4.3 Vortex ring state region

The VRS is characterized by the presence of a vortex ring around the blade tips. We expect to see a thrust loss and a power increase. This regime is particularly dangerous since the collective command isn't acting as wanted: increasing it will make the vortex ring faster, and will thus reinforce it. This regime must absolutely be avoided by pilots.

To obtain better statistics and smoother plots, all the simulations of this sections have been extended to 130 s with 40 recordings of the velocity and the vorticity per second on both the xz - and the yz -planes. It permits to have a dataset of 4800 vector fields for our averages.

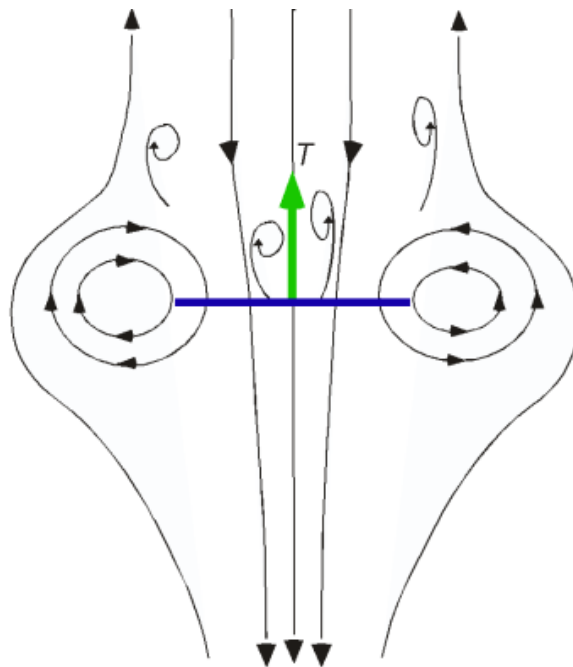


Figure 4.15: Theoretic streamlines expectation

©[17]

4.3.1 $V_C + \epsilon_C = -9\text{m/s}$

We can tell, by looking at the streamlines (figure 4.17a), that the vortex is now at the blade level: we are in VRS. As expected, the thrust shows a lowered value (89% of the T_h)⁷. But the power has decreased (78 % of the P_h)⁷, even if we expected the opposite. More interesting: the flapping angle (in pink on figure 4.16) is now below the hover one (81 % of β_h)⁷ and it seems to have “calmed down”, showing way smaller vibrations of the blades than before.

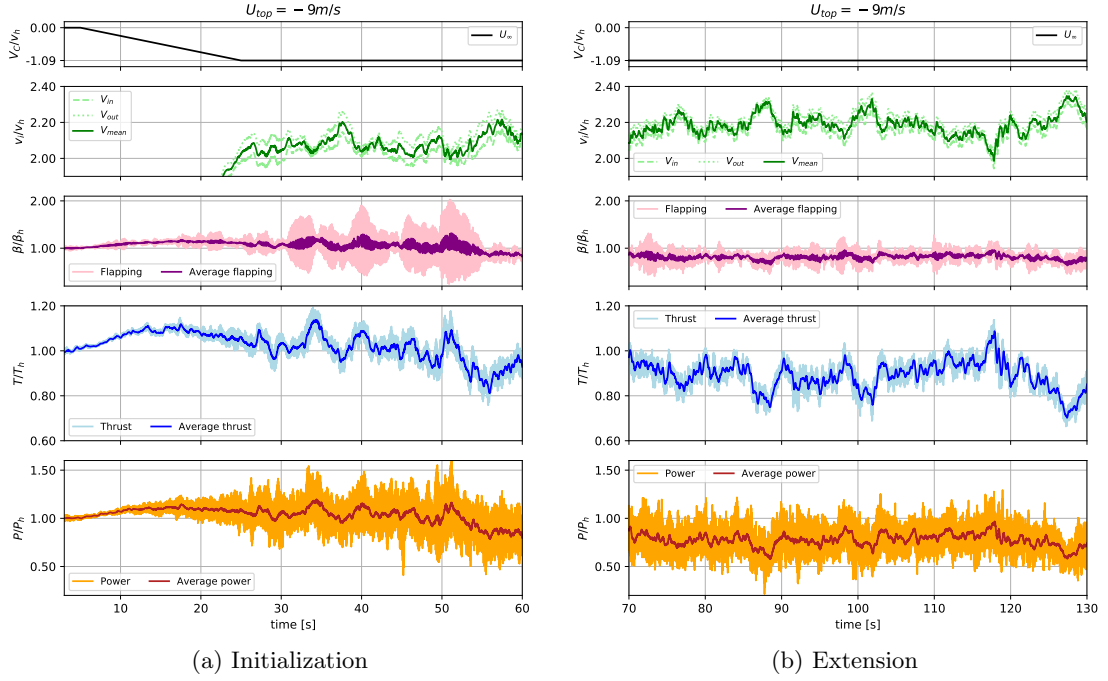


Figure 4.16: Descend at $V_C + \epsilon_C = -9 [\text{m s}^{-1}]$

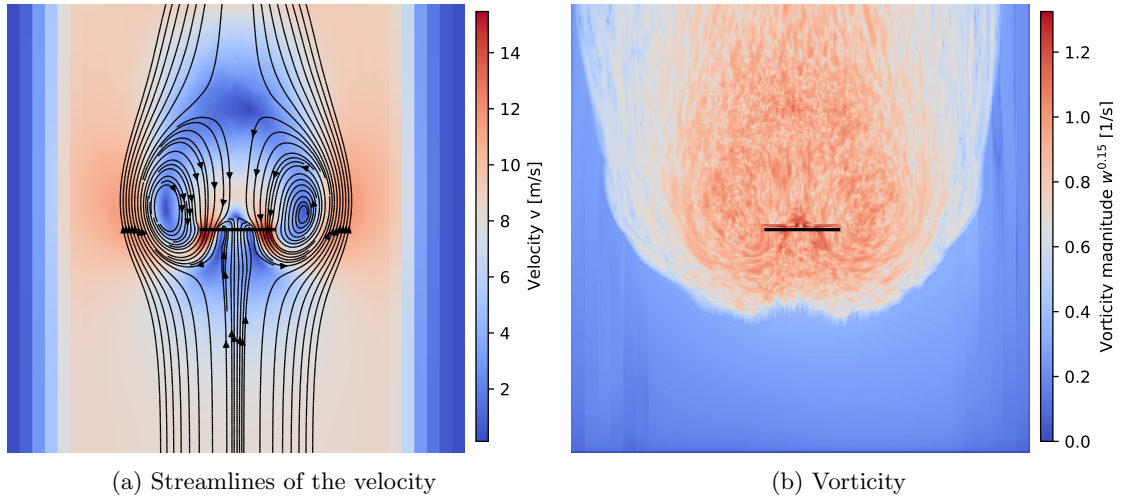


Figure 4.17: Time-average field of the xz - and the yz -planes combined [70s - 130s], 40 measures/s (4800 data)

⁷Average on the last 30 s

4.3.2 $V_C + \epsilon_C = -9.5\text{m/s}$

We see a very similar evolution than on the previous simulation. A thing that draw attention is that V_{in} and V_{out} (light green curves on figure 4.18) are now nearly identical, showing that the flow is now completely normal to the rotor plane.

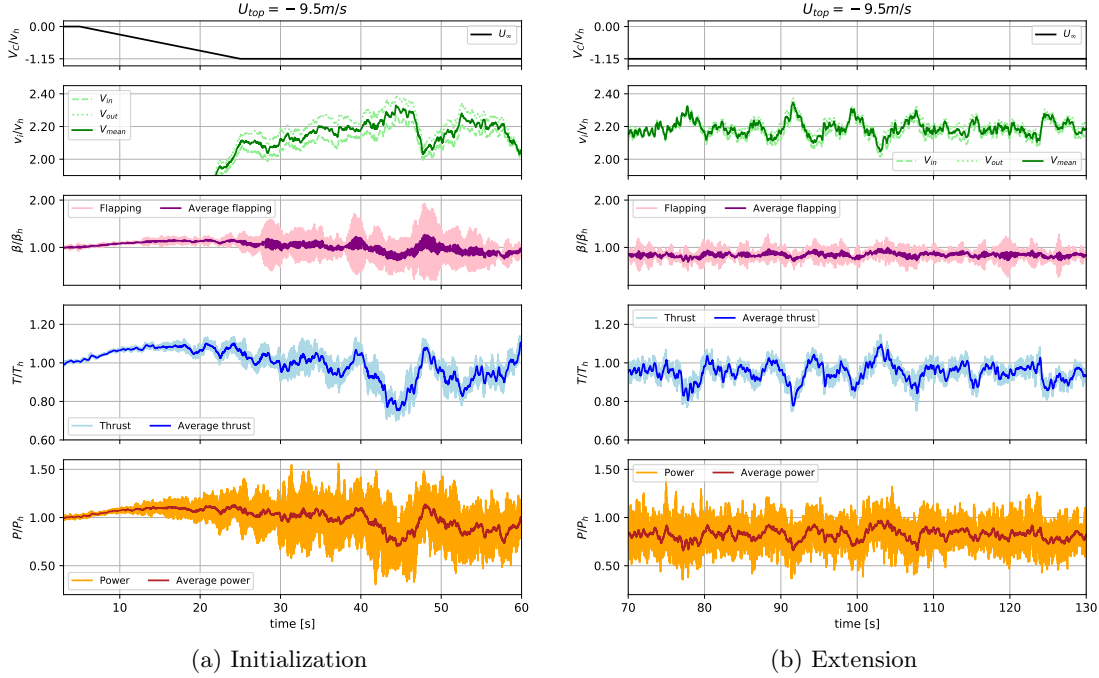


Figure 4.18: Descend at $V_C + \epsilon_C = -9.5 [\text{m s}^{-1}]$

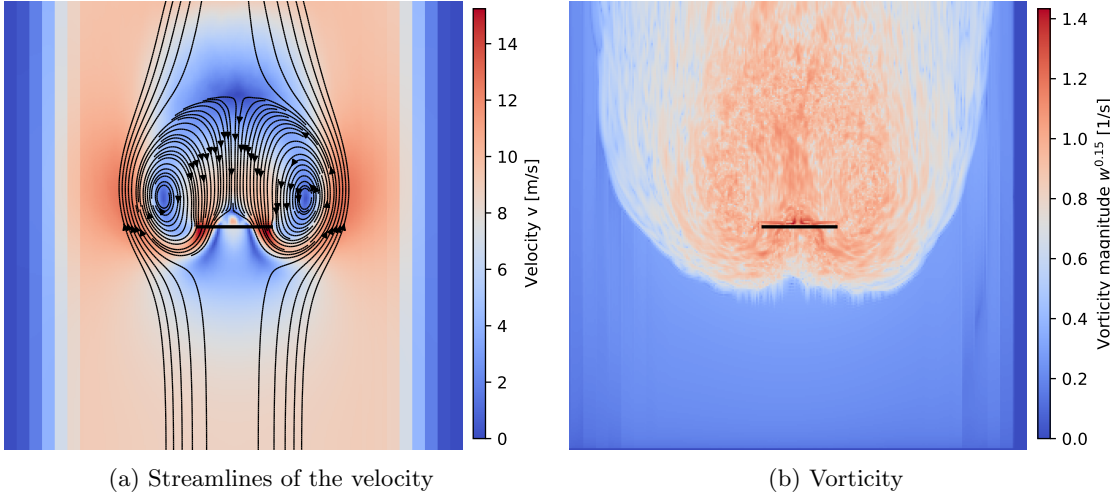


Figure 4.19: Time-average field of the xz - and the yz -planes combined
[70s – 130s], 40 measures/s (4800 data)

4.3.3 $V_C + \epsilon_C = -10\text{m/s}$

The observations stay unchanged in this simulation. Let's just notice that the vortex ring is getting higher on the rotor plane.

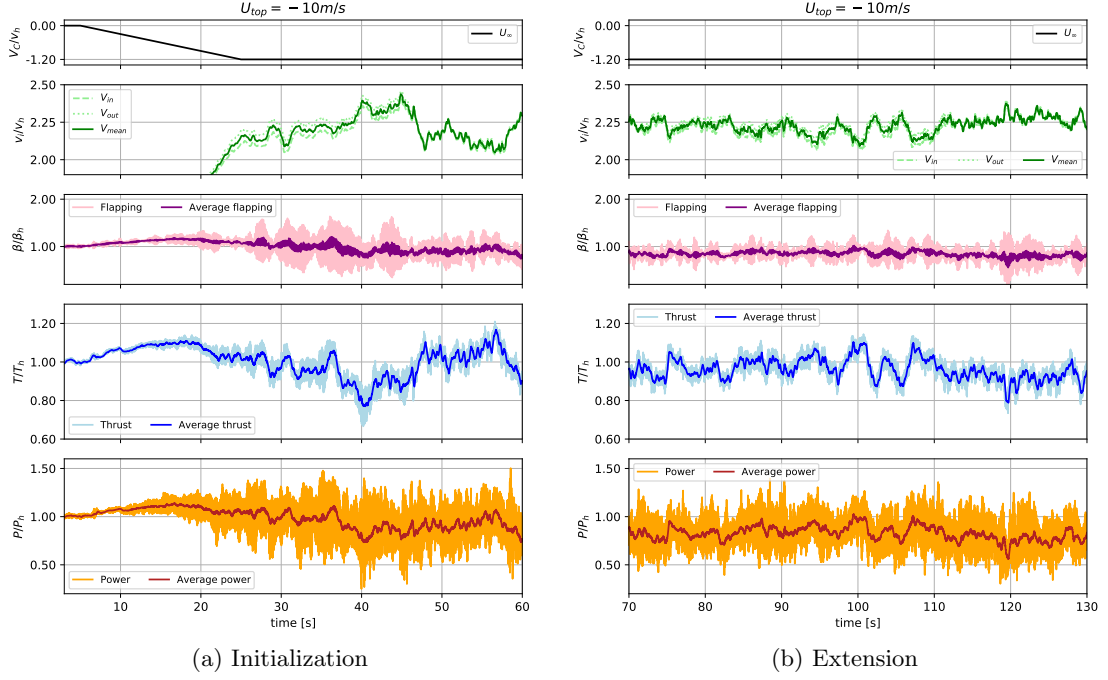


Figure 4.20: Descend at $V_C + \epsilon_C = -10 [\text{m s}^{-1}]$

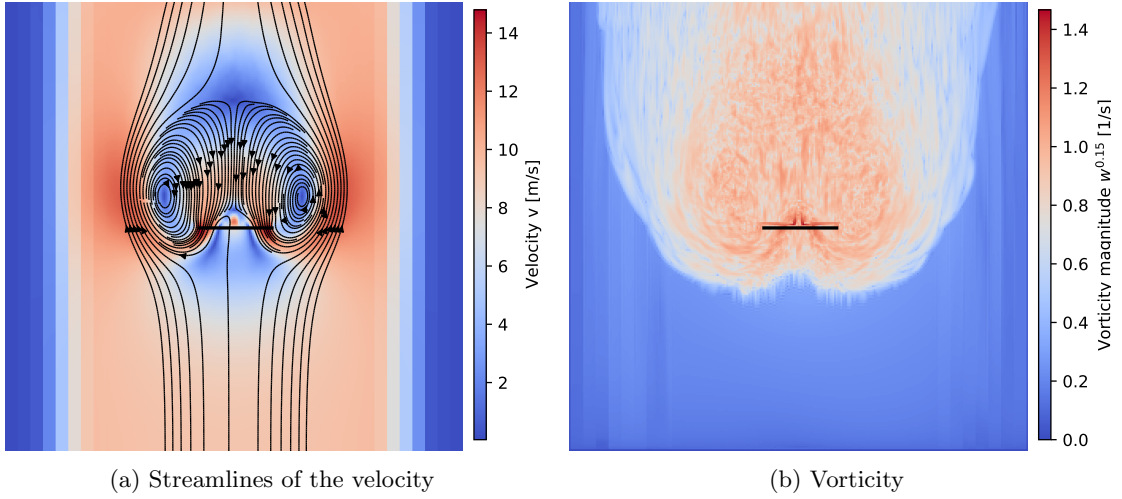


Figure 4.21: Time-average field of the xz - and the yz -planes combined [70s – 130s], 40 measures/s (4800 data)

4.3.4 $V_C + \epsilon_C = -11\text{m/s}$

The vortex ring is now nearly completely above the rotor plane. We can also tell that the thrust is back at the hover value (101% of T_h)⁸.

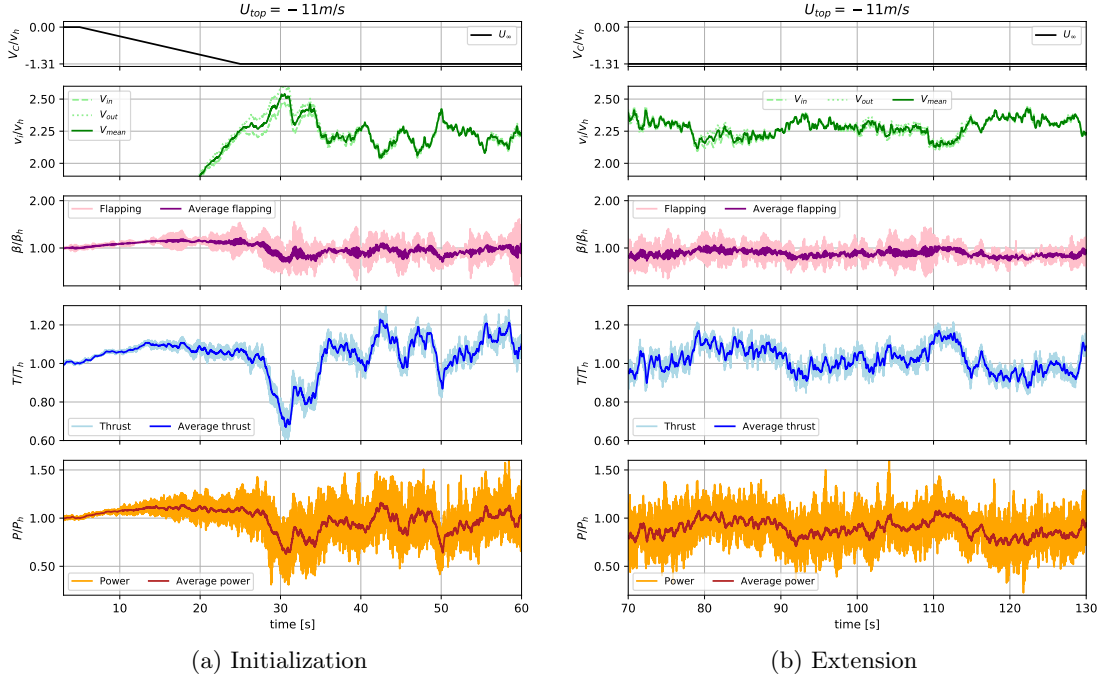


Figure 4.22: Descend at $V_C + \epsilon_C = -11 [\text{m s}^{-1}]$

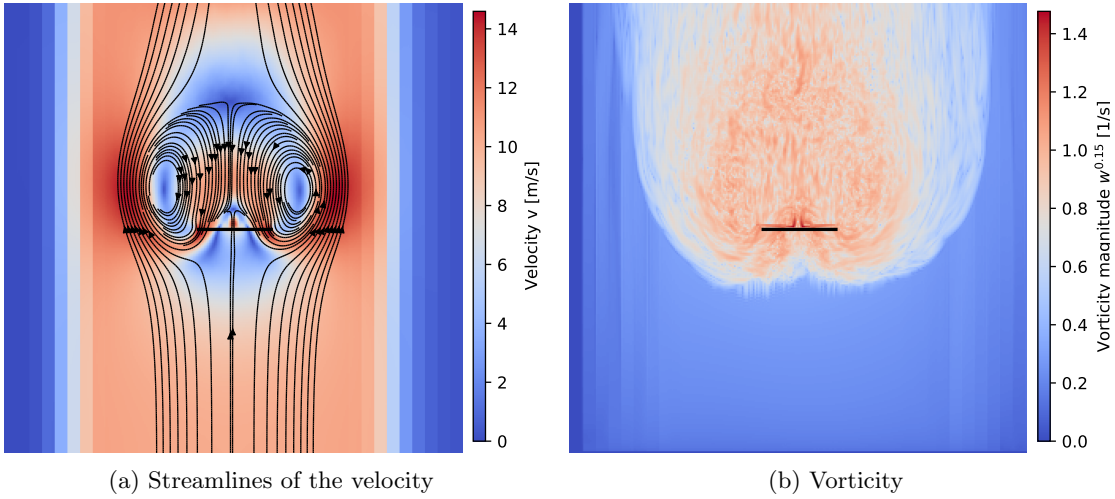


Figure 4.23: Time-average field of the xz - and the yz -planes combined [70s - 130s], 40 measures/s (4800 data)

⁸Average on the last 30 s

4.3.5 $V_C + \epsilon_C = -12\text{m/s}$

This simulation is the limit case of VRS. We can clearly see a “peak” around 30s, it will be discussed in chapter 5. Otherwise, we see that the thrust is now above the hover one (110 % of T_h)⁹. The power is back to the hover value (98 % of P_h)⁹ and so is the flapping (95 % of β_h)⁹.

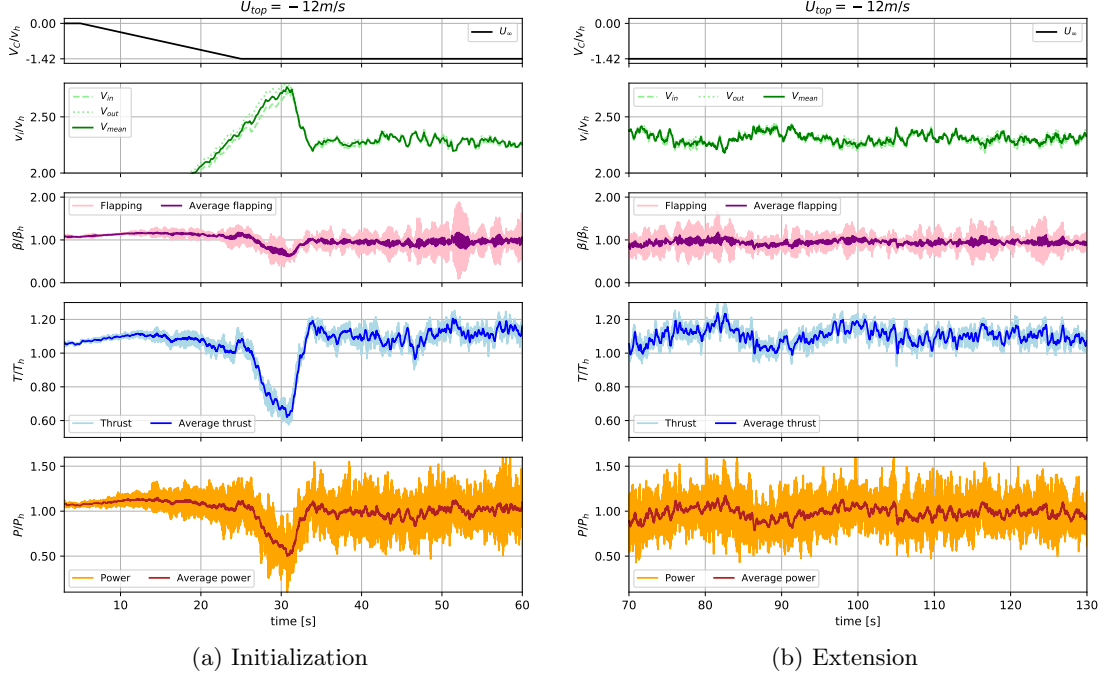


Figure 4.24: Descend at $V_C + \epsilon_C = -12 [\text{m s}^{-1}]$

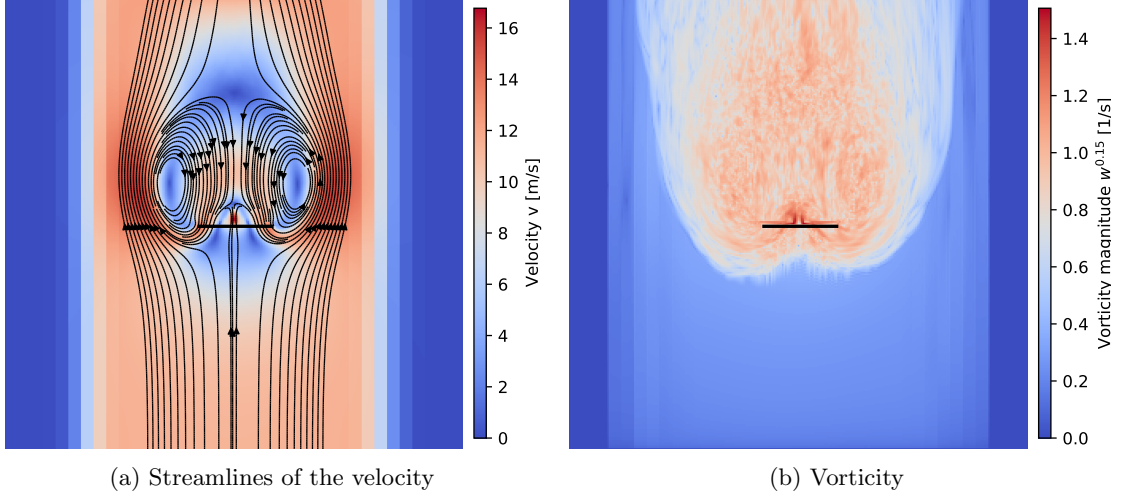


Figure 4.25: Time-average field of the xz - and the yz -planes combined [70s - 130s], 40 measures/s (4800 data)

⁹ Average on the last 30s

4.4 Turbulent wake state region

The turbulent wake state region (that we will call TWS from now), is described as the region where the recirculations take place above the rotor plane. From a pilot's perspective, this regime means that the collective command works again. But TWS is still a very unsteady flight regime and should also be avoided.

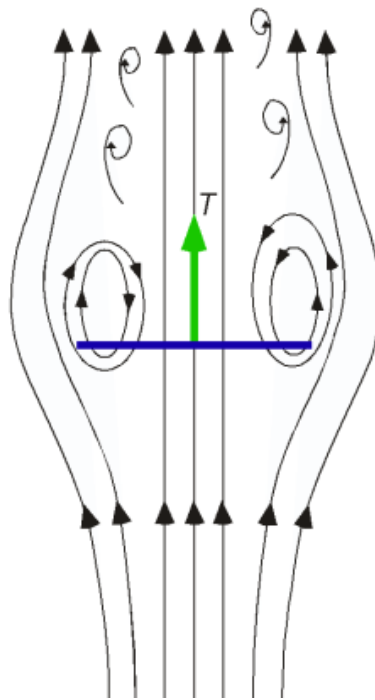


Figure 4.26: Theoretic streamlines expectation

©[17]

4.4.1 $V_C + \epsilon_C = -14\text{m/s}$

The differences between this simulation and those that were held in VRS are the noticeable increase of the thrust (130 % of T_h)¹⁰ and of power (124% of P_h)¹⁰ with the return of the vibrations of the flapping (in pink on figure 4.27).

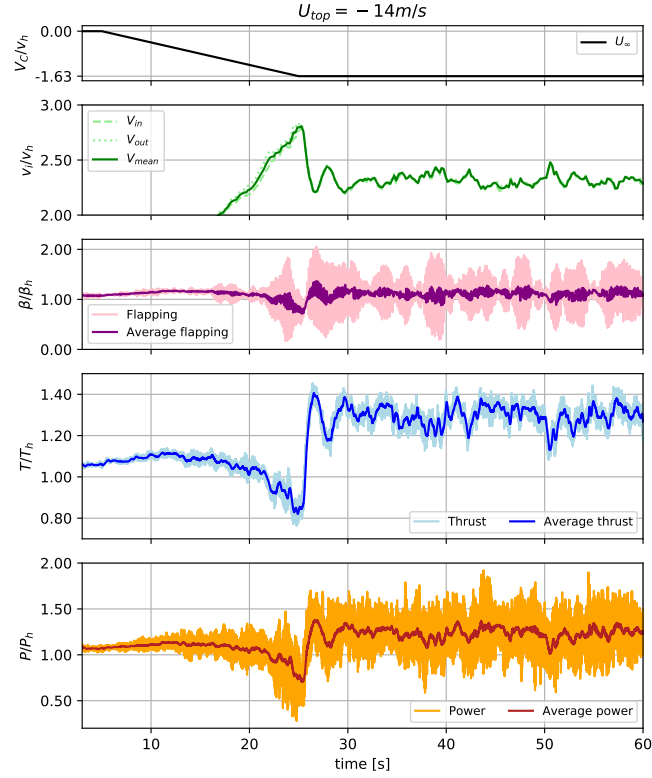


Figure 4.27: Descend at $V_C + \epsilon_C = -14 [\text{m s}^{-1}]$

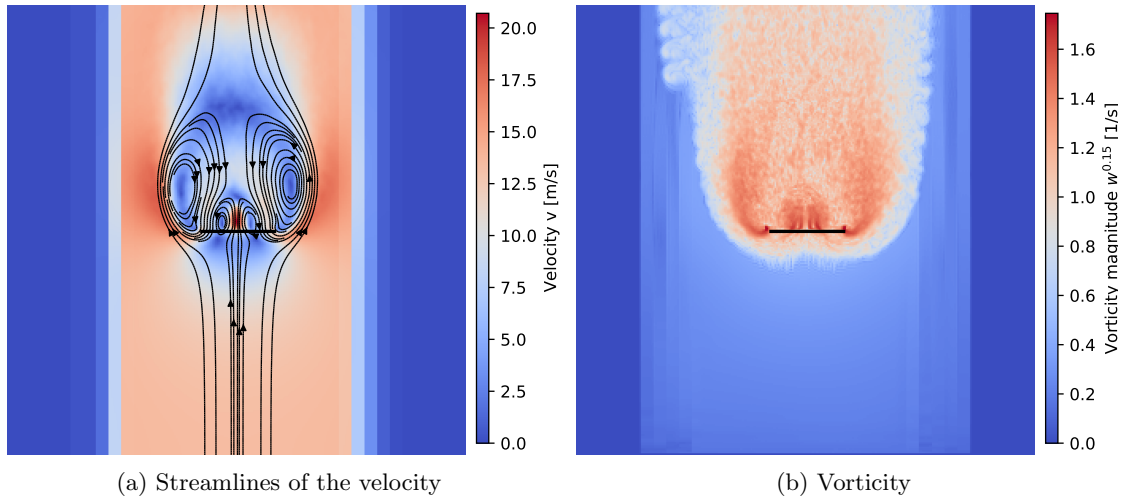


Figure 4.28: Time-average field of the yz -plane [30s-60s], 5 measures/s (150 data)

¹⁰ Average on the last 30s

4.4.2 $V_C + \epsilon_C = -16\text{m/s}$

All the observations of section 4.4.1 stay valid here. Moreover, we can add that the flapping angle is now above the hover one (130 % of β_h)¹¹. This shows that the rotor is braking again and proves that we aren't in VRS anymore.

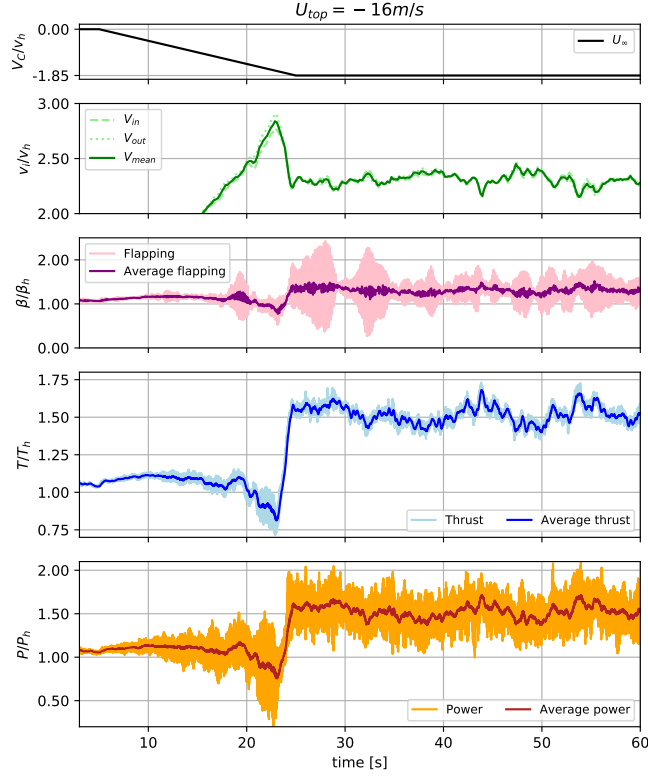


Figure 4.29: Descend at $V_C + \epsilon_C = -16 [\text{m s}^{-1}]$

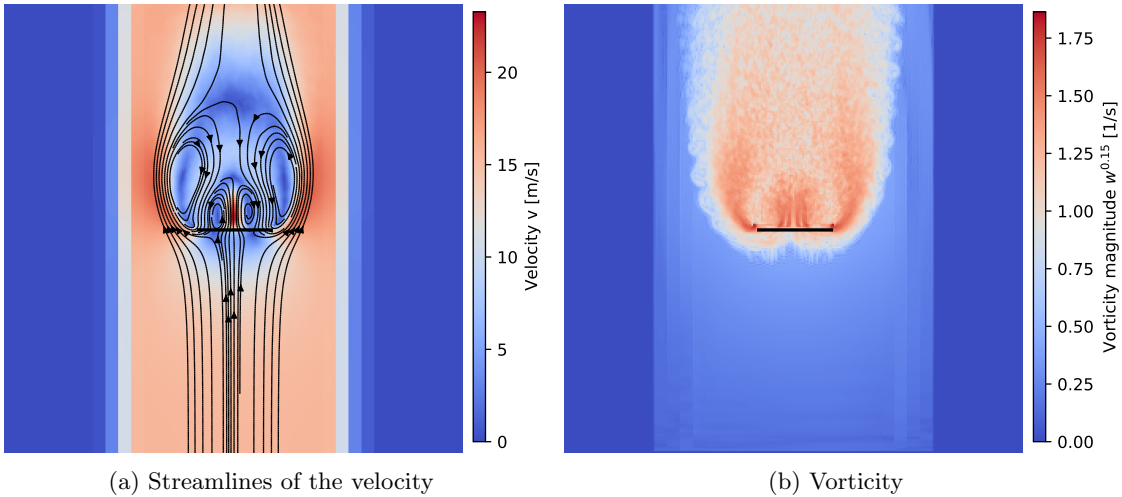


Figure 4.30: Time-average field of the yz -plane [30s-60s], 5 measures/s (150 data)

¹¹Average on the last 30s

4.4.3 $V_C + \epsilon_C = -18\text{m/s}$

This case is the limit case of TWS. The unsteadiness of our curves (figure 4.31) begin to disappear as the recirculations are now completely above the rotor plane. We see that V_{mean} , V_{in} and V_{out} are still combined, showing that the flow is still normal to the plane.

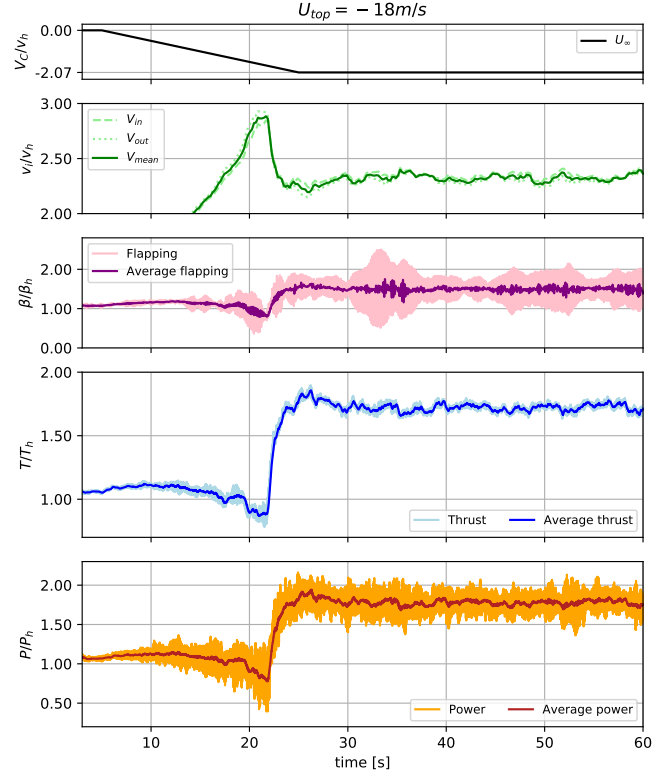


Figure 4.31: Descend at $V_C + \epsilon_C = -18 [\text{m s}^{-1}]$

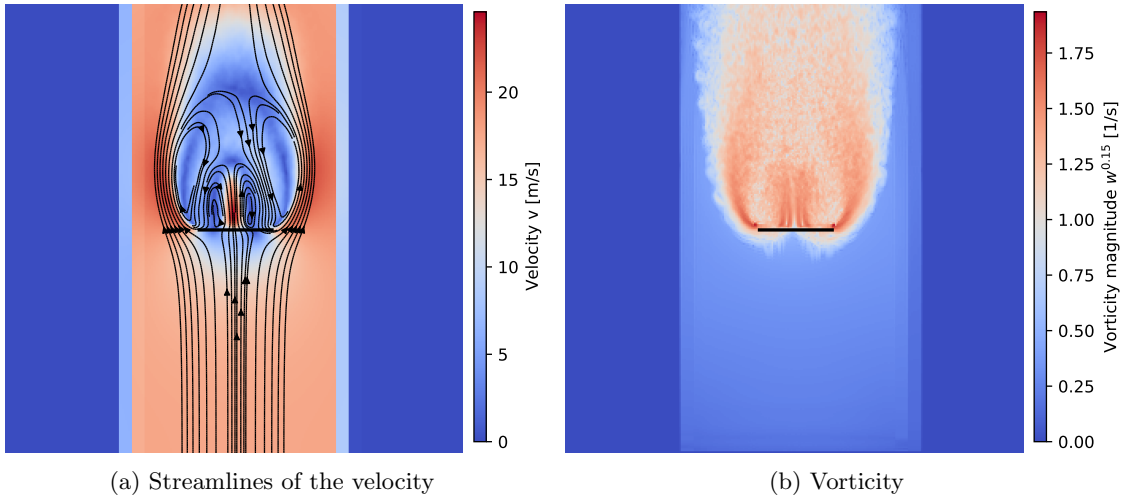


Figure 4.32: Time-average field of the yz -plane [30s-60s], 5 measures/s (150 data)

4.5 Windmill brake state region

The windmill brake state (WBS from now) is characterized by an inversion of the flow direction at the rotor plane. We can tell that the theoretic streamlines below (figure 4.33) are indeed exactly the same as the one of the stable region (figure 4.4) aside from the direction. This regime is again a stable regime but it correspond to a very fast descend. In real flight operation, this regime is used for emergency situations like the lost of the engine[5]. The rotor will act like a windmill, slowing down the flux to generate thrust.

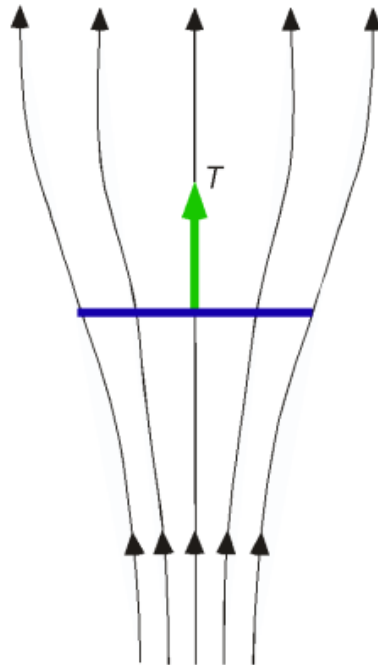


Figure 4.33: Theoretic streamlines expectation

©[17]

4.5.1 $V_C + \epsilon_C = -20\text{m/s}$

Multiple things jump to mind when looking at the curves hereunder. Firstly, the power is twice the hover value (206% of P_h)¹², this is due to the braking behavior of this regime. The flapping has become considerably higher (171 % of β_h)¹² and is particularly unsteady. As we observed with the limit case Stable/VRS (section 4.2.5), this is due to the direct proximity of the recirculations with the rotor plane.

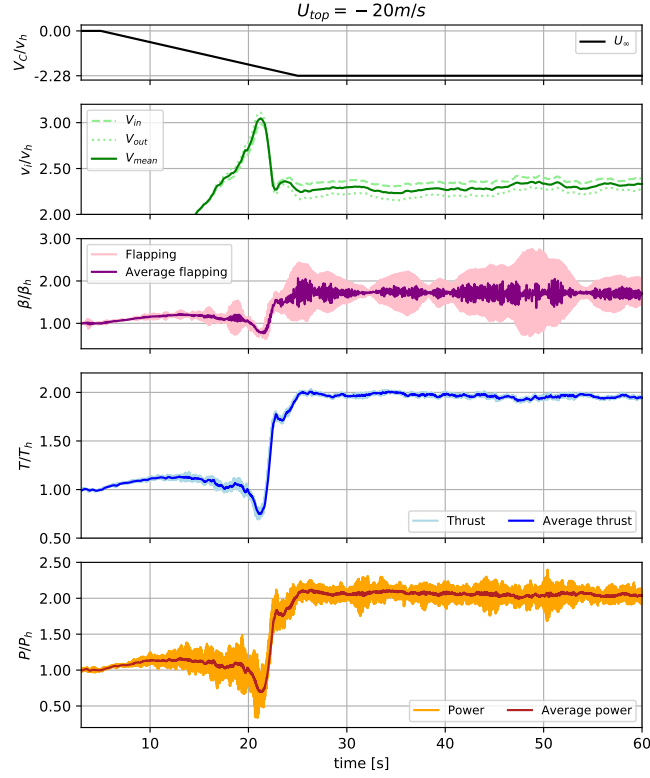


Figure 4.34: Descend at $V_C + \epsilon_C = -20 [\text{m s}^{-1}]$

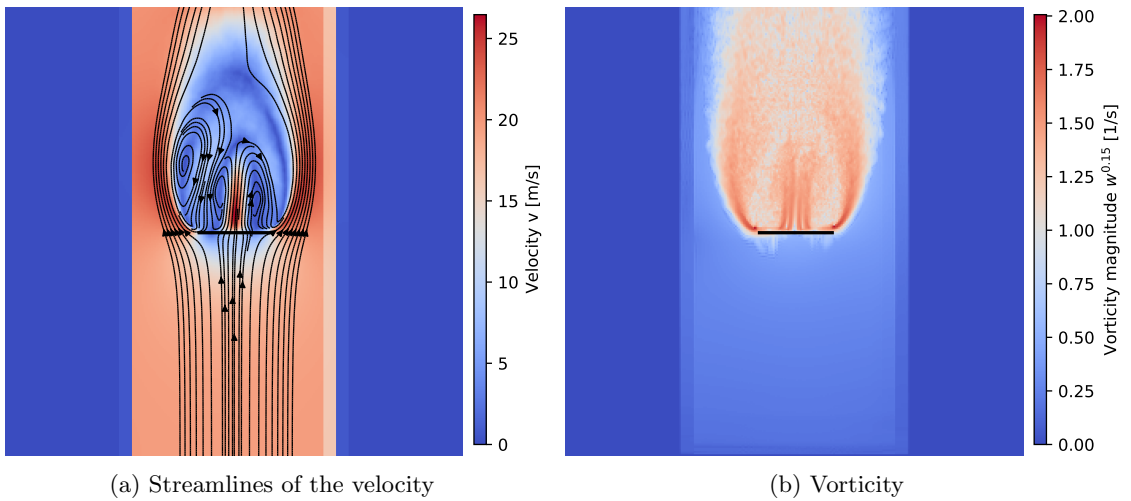


Figure 4.35: Time-average field of the yz -plane [30s-60s], 5 measures/s (150 data)

¹² Average on the last 30s

4.5.2 $V_C + \epsilon_C = -22\text{m/s}$

A very interesting thing to notice here is that we now have a noticeable difference between V_{in} and V_{out} again (light green curves on figure 4.36). In other words, we have again a non-normal flow at the rotor plane.¹³ We can easily be convince of that by having a look at the streamlines.

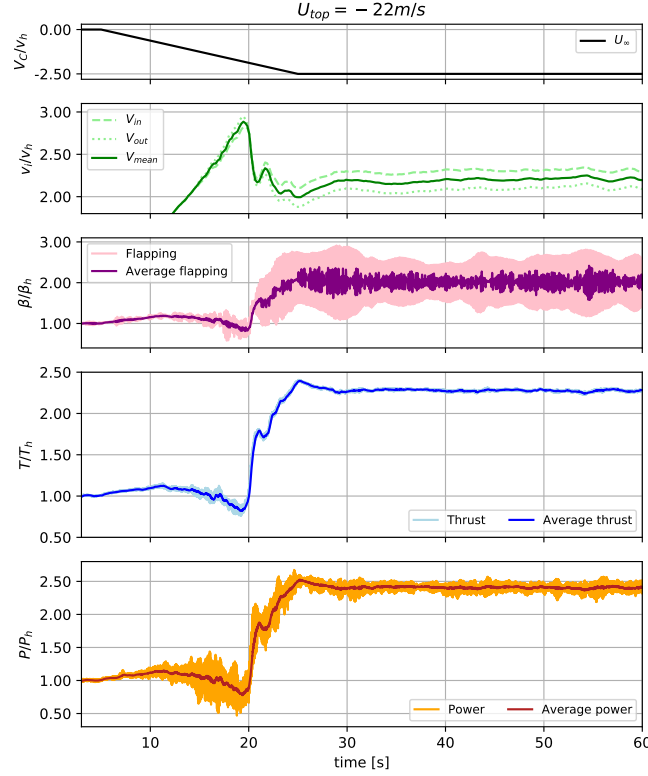


Figure 4.36: Descend at $V_C + \epsilon_C = -22 [\text{m s}^{-1}]$

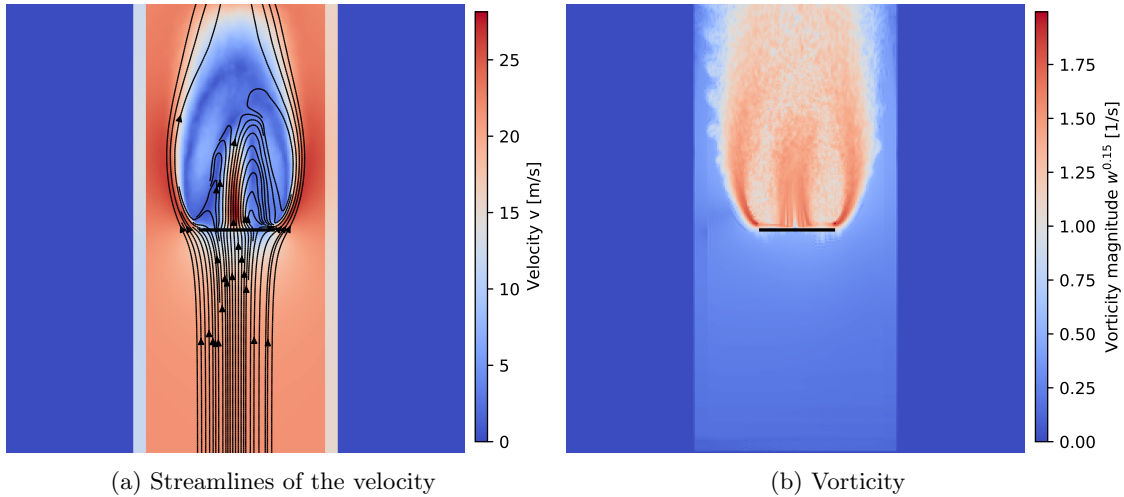


Figure 4.37: Time-average field of the yz -plane [30s-60s], 5 measures/s (150 data)

¹³Note: on the graph, we read $V_{in} > V_{out}$. As reminder, V_{in} is the slice above the rotor, it should thus be slower than V_{out} . But since the net induced velocities are now negative, and that the graph shows the total induced velocities ($v_{i,net} + V_C$), while being smaller in absolute value, V_{in} appears to be greater here.

4.5.3 $V_C + \epsilon_C = -24\text{m/s}$

In addition to the previous observations, we see that the power continues to increase. In this regime, the flow is giving so much energy to the rotor that we could stop the engine. This is the principle of *autorotation*¹⁴ but it is beyond of the scope of this thesis so we will not discuss it further.

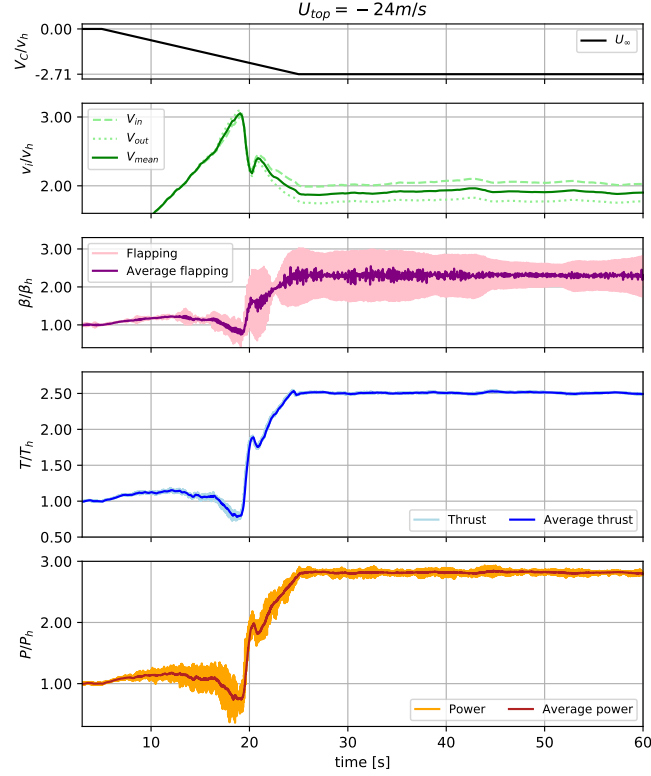


Figure 4.38: Descend at $V_C + \epsilon_C = -24\text{ [m s}^{-1}\text{]}$

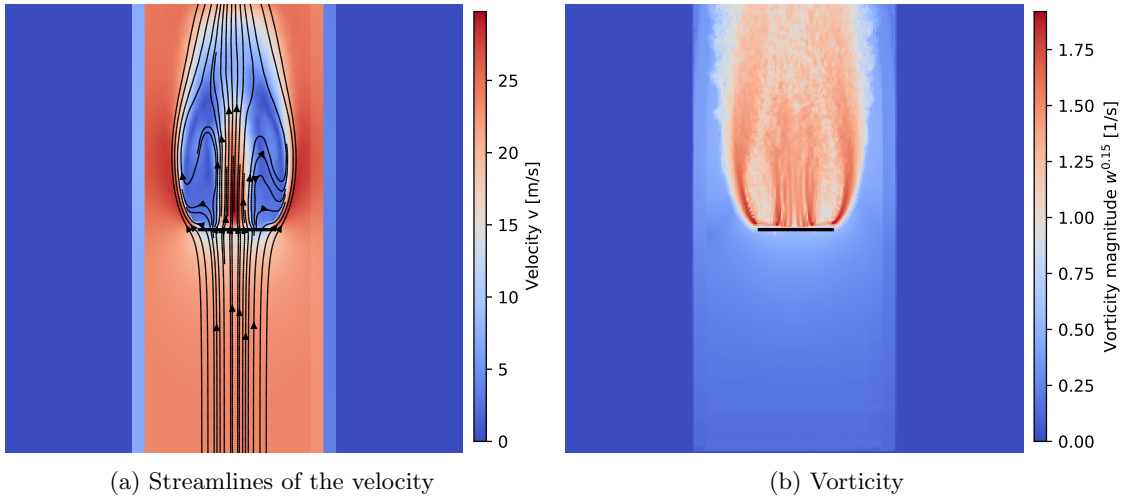


Figure 4.39: Time-average field of the yz -plane [30s-60s], 5 measures/s (150 data)

¹⁴To do so, we should reverse our collective, otherwise, in real operation, the rotation direction of the rotor would be inverted, which is undesired.

4.5.4 $V_C + \epsilon_C = -26\text{m/s}$

A very interesting thing happens here: we observe a perfect convergence of all the curves. We are now totally in WBS such that the vortex of a blade doesn't interact with the one of the previous blade anymore. A look at the average vorticity (figure 4.41b) shows a cylinder of vorticity that is approximately half the diameter of the rotor. Due to our pitch angle that is clearly not adapted to this regime, the angle of attack near the hub has become too large: the boundary layer has detached in this region. If we look at the other simulations around this one, we see that the more we decrease the inflow, the more this cylinder gets wide, illustrating the displacement of the critical angle of attack (see appendix B.1 for the 3D wakes).

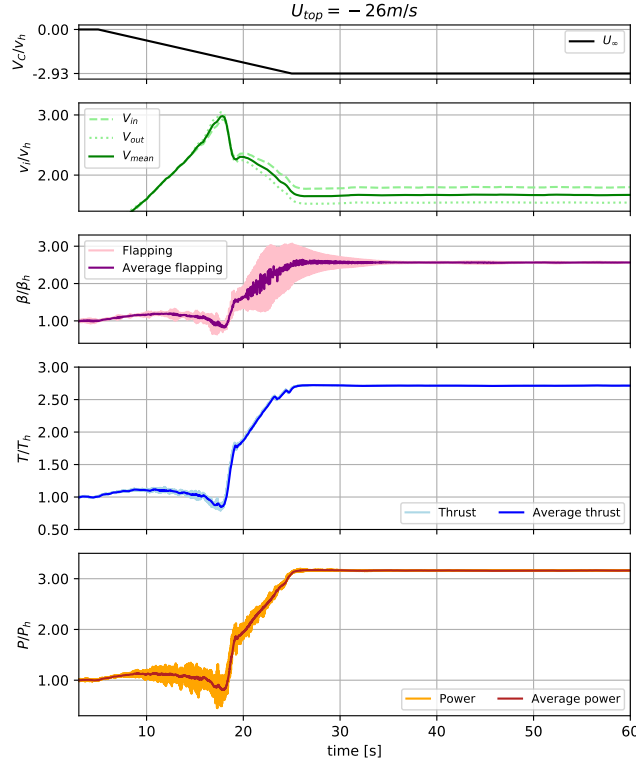


Figure 4.40: Descend at $V_C + \epsilon_C = -26 [\text{m s}^{-1}]$

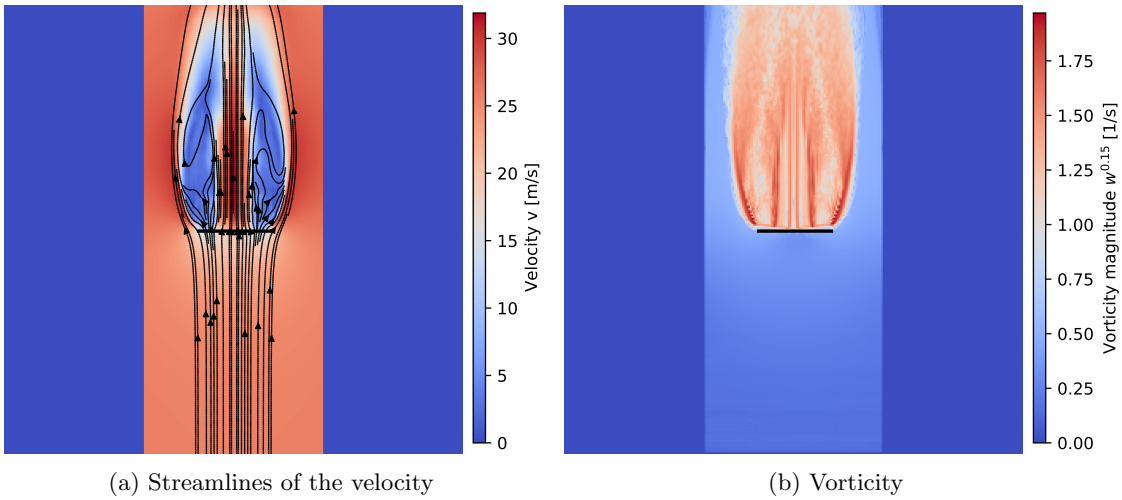


Figure 4.41: Time-average field of the yz -plane [30s-60s], 5 measures/s (150 data)

4.5.5 $V_C + \epsilon_C = -28\text{m/s}$

We observe here an even faster convergence that begins directly at the very end of the ramp (25s). The VRS and the TWS appear in the intervals [15s-18s] and [18s-20s] respectively.

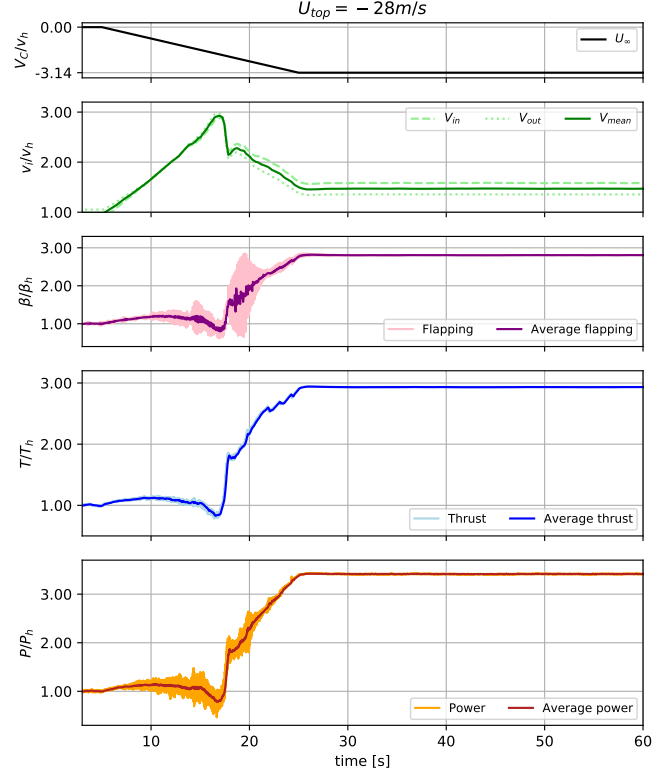


Figure 4.42: Descend at $V_C + \epsilon_C = -28\text{ [m s}^{-1}\text{]}$

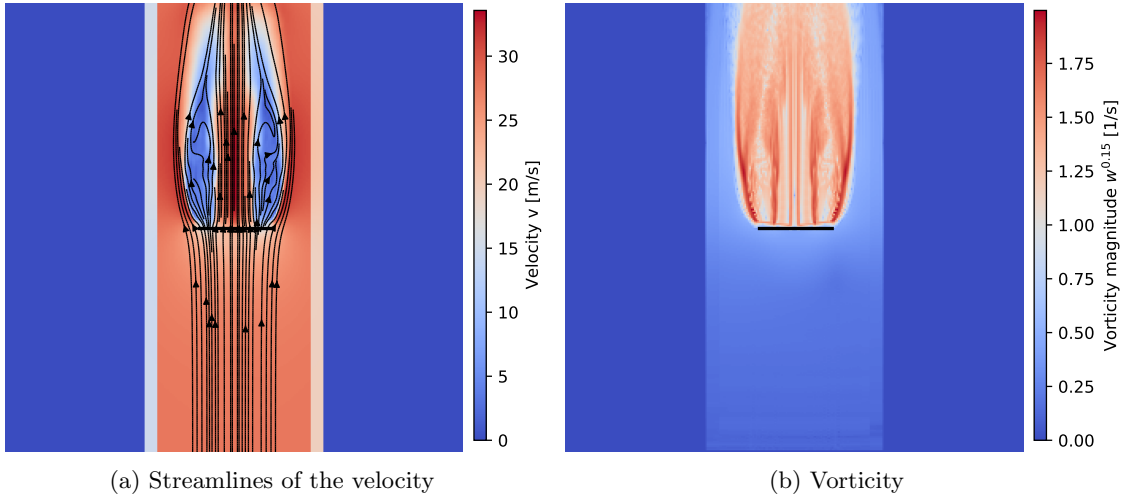


Figure 4.43: Time-average field of the yz -plane [30s-60s], 5 measures/s (150 data)

4.5.6 $V_C + \epsilon_C = -30\text{m/s}$

We see here that the streamlines begin to align themselves. Getting really close to the theoretic expectation (figure 4.33).

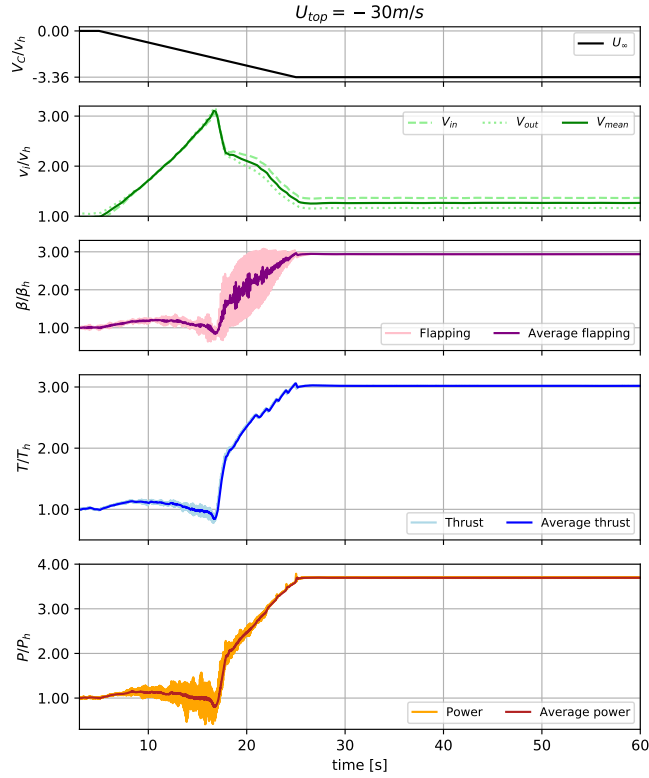


Figure 4.44: Descend at $V_C + \epsilon_C = -30 [\text{m s}^{-1}]$

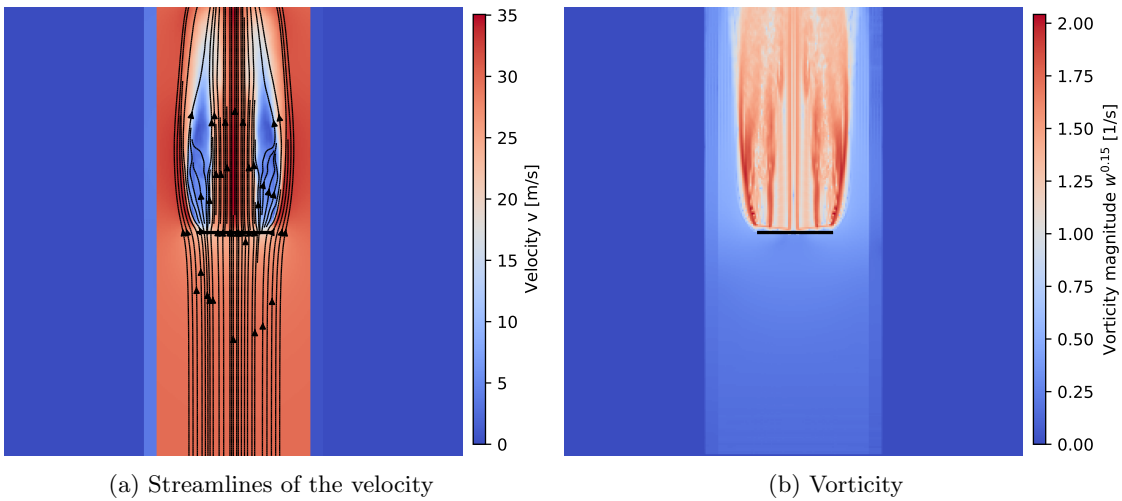


Figure 4.45: Time-average field of the yz -plane [30s-60s], 5 measures/s (150 data)

4.5.7 $V_C + \epsilon_C = -32\text{m/s}$

This is our last simulation. It is held at an extremely high descend rate. So high that even the hub creates a wake. We can thus see on figure 4.47b 3 vortex cylinders, from: the hub, the limit of the boundary layer detachment and the tip¹⁵. We will not go further, since, due to our inappropriate pitch, the required power would be higher than the maximal allowed power of our helicopter. A revised pitch, adapted to WBS, would show a negative value of the power.

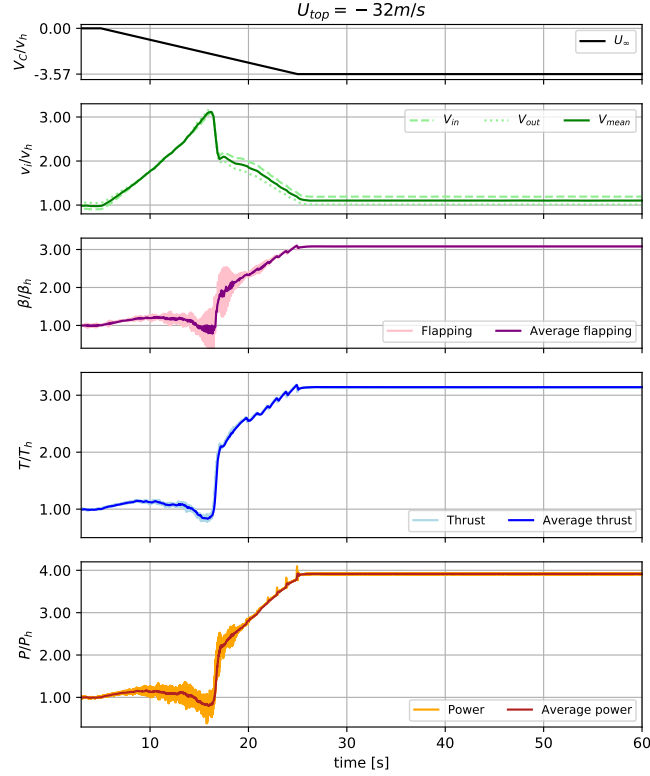


Figure 4.46: Descend at $V_C + \epsilon_C = -32 [\text{m s}^{-1}]$

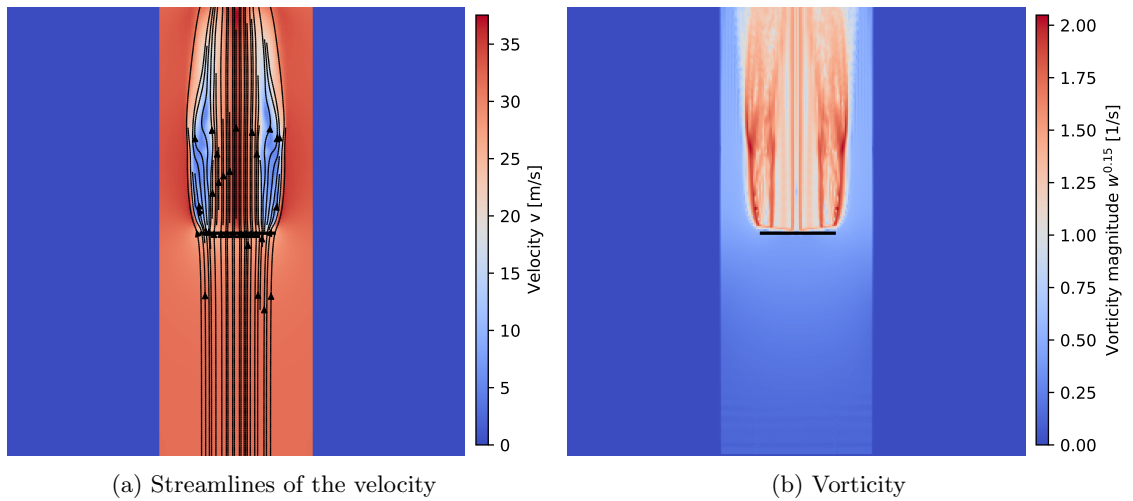


Figure 4.47: Time-average field of the yz -plane [30s-60s], 5 measures/s (150 data)

¹⁵Note: the flapping angle is now so high that we can clearly see the conical shape of the blades above the black line I put to represent the rotor.

4.6 Summary

Through the four last sections, we explored the whole set of phenomena that one can encounter in descend flight. Let's summarize the key elements of each regime.

Stable region

The stable region is the one where the wake remains below the rotor plane. The main characteristics of this region are:

- A progressive increase of the induced velocity;
- A slight increase of the thrust;
- An increase of the required power;
- A slight increase of the flapping angle;
- A very vibrating system.

Vortex ring state region

The VRS happens when the wake reaches the rotor plane, forming a vortex ring around the blade tips. We can describe it with:

- A relatively constant induced speed (around $v_i/V_C = 2.2$);
- An unsteady thrust, globally below the hover thrust;
- A decrease of the power;
- A sudden decrease of the flapping angle;
- A sudden reduction of the vibrations of the blades.

Turbulent wake state region

The TWS is the region where the wake takes place above the rotor plane. Its characteristics are:

- A sudden decrease of the induced velocity;
- A sudden increase of the thrust;
- A sudden increase of the power (that wouldn't be the case with an adapted pitch);
- A sudden increase of the flapping angle;
- Again some noticeable vibrations on the blades.

Windmill brake state region

The WBS is the region where the descend rate is high enough to invert the flow direction in the rotor plane. Its description is:

- A progressive decrease of the induced velocity;
- A progressive increase of the thrust;
- A progressive increase of the power (it should be the opposite, again, due to our pitch);
- A progressive increase of the flapping angle;
- An incredible reduction of the vibrations, leading to a perfect convergence.

4.7 Plots of the descend path curves

By reporting the induced velocity and the power of each simulation we get the following:

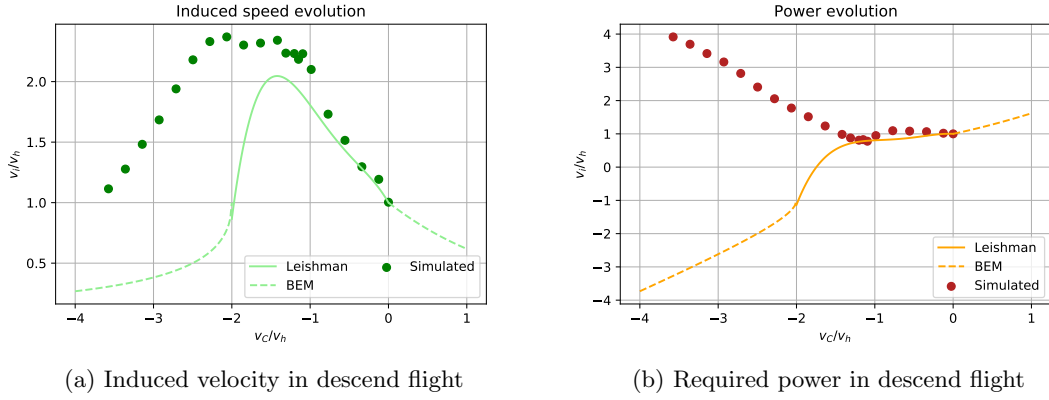


Figure 4.48: Comparisons of the simulations with the theoretic expectation

We can tell that, while being really close to the expectations on slow descend rates, at higher descend rates, we are absolutely not on the desired path. An explanation is that to plot this graph, we are assuming constant speed descend. But, by the first Newton's law, that means that the thrust should be constant too. We can tell that it is not the case. One can thus apply thrust-based correction factors that we will name ξ .

We have from section 1.3 that:

$$T \propto v_i^2 \iff v_i \propto \sqrt{T} \quad (4.7)$$

We can thus create our correction factors for each simulation:

$$\xi = \sqrt{T} \quad (4.8)$$

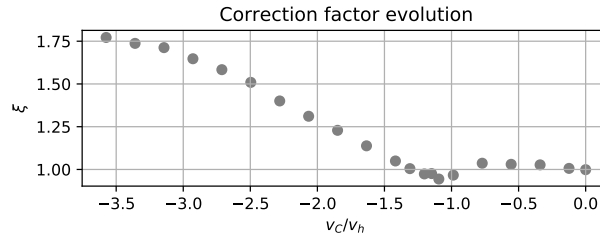


Figure 4.49: Thrust-based correction factors

Then, adding equation 1.14, we have:

$$\left. \frac{v_i}{v_h} \right|_{new} = \left. \frac{v_i}{v_h} \right|_{old} \cdot \xi \quad (4.9)$$

$$\left. \frac{P}{P_h} \right|_{new} = \left. \frac{P}{P_h} \right|_{old} - \frac{v_i}{v_h} (1 - \xi) \quad (4.10)$$

We obtain:

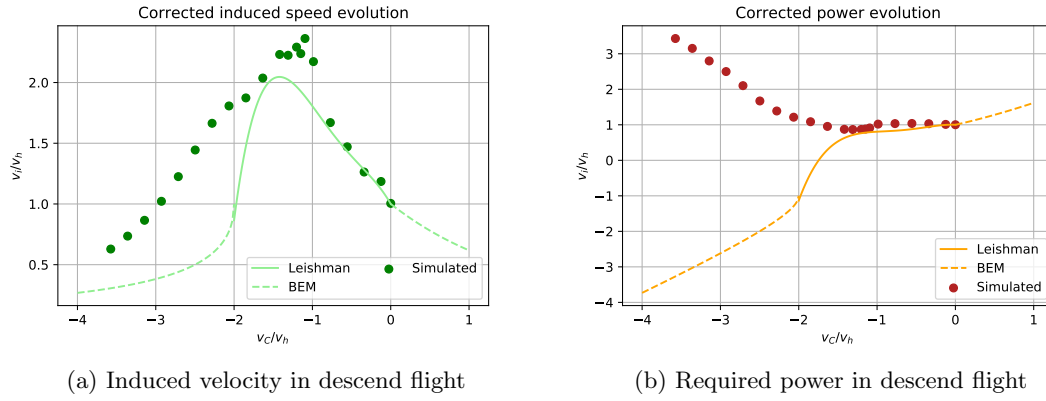


Figure 4.50: Corrected comparisons of the simulations with the theoretic expectation

The curve of the induced speed is more convincing even if we don't get to the correct path. But the power curve is hardly better. Let's remind that our pitch angle was fixed for the hover and certainly not for WBS. Indeed, in our configuration, we are struggling against the flow. In reality, this would be a very violent braking. Even our correction factors cannot manage that. We must use an adapted pitch to have a valid WBS. Hereunder (figures 4.51, 4.52 and 4.53) are three simulations that were ran with an arbitrary pitch of $\theta = -0.35[\text{rad}] \simeq -20[^\circ]$, it leads to a correct WBS:

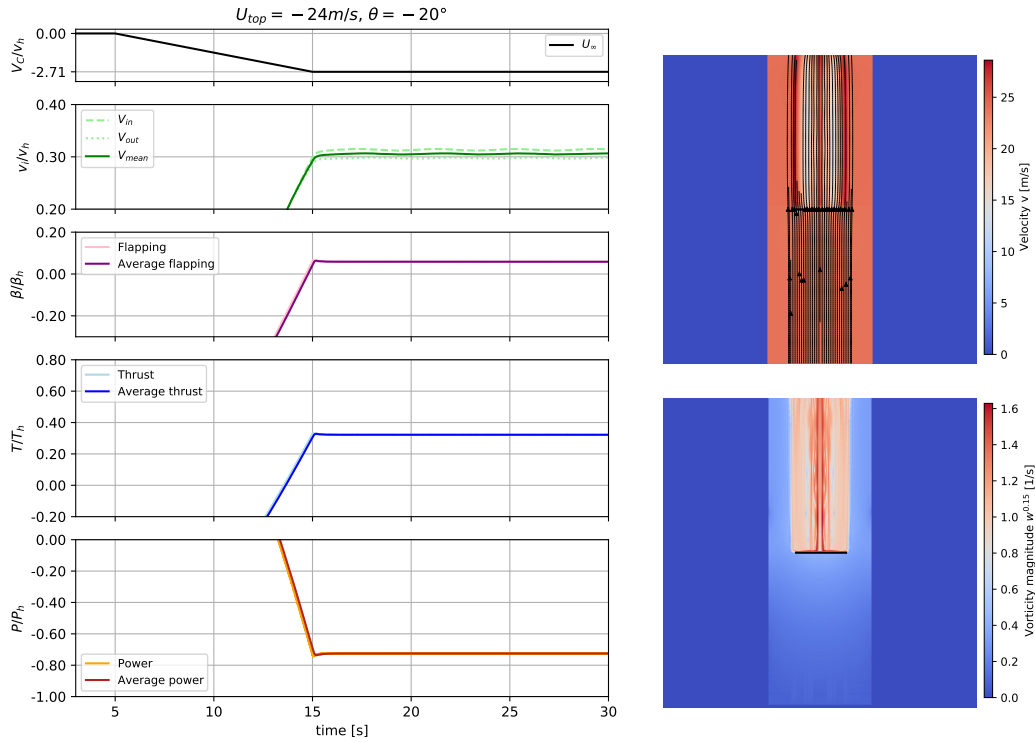
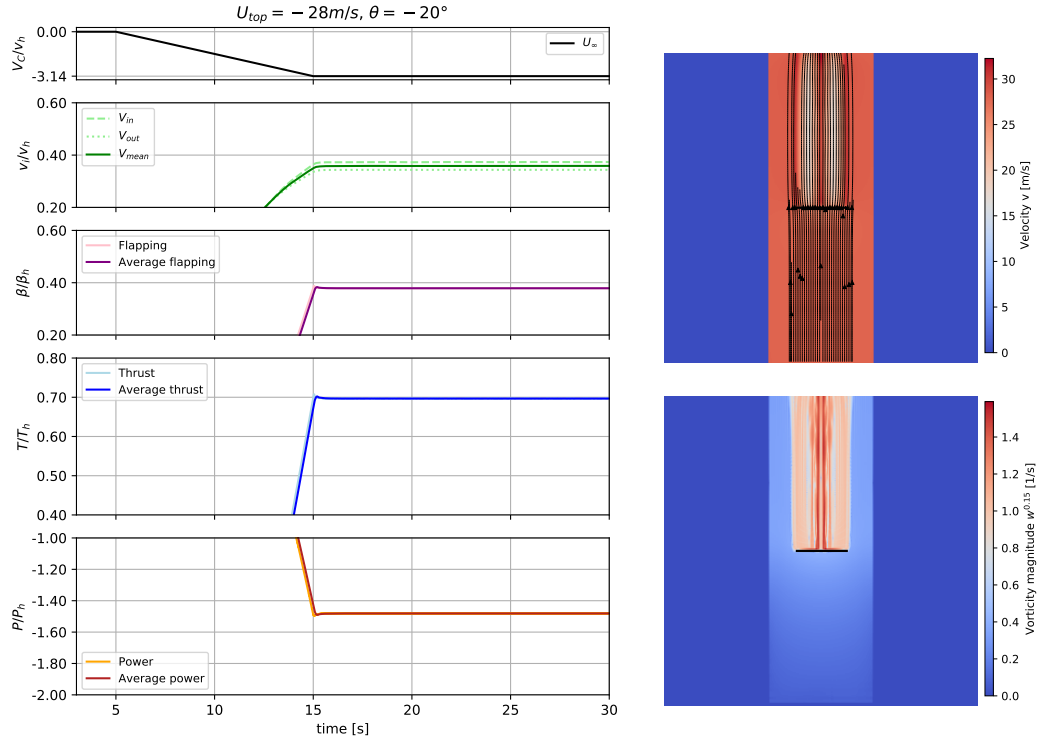
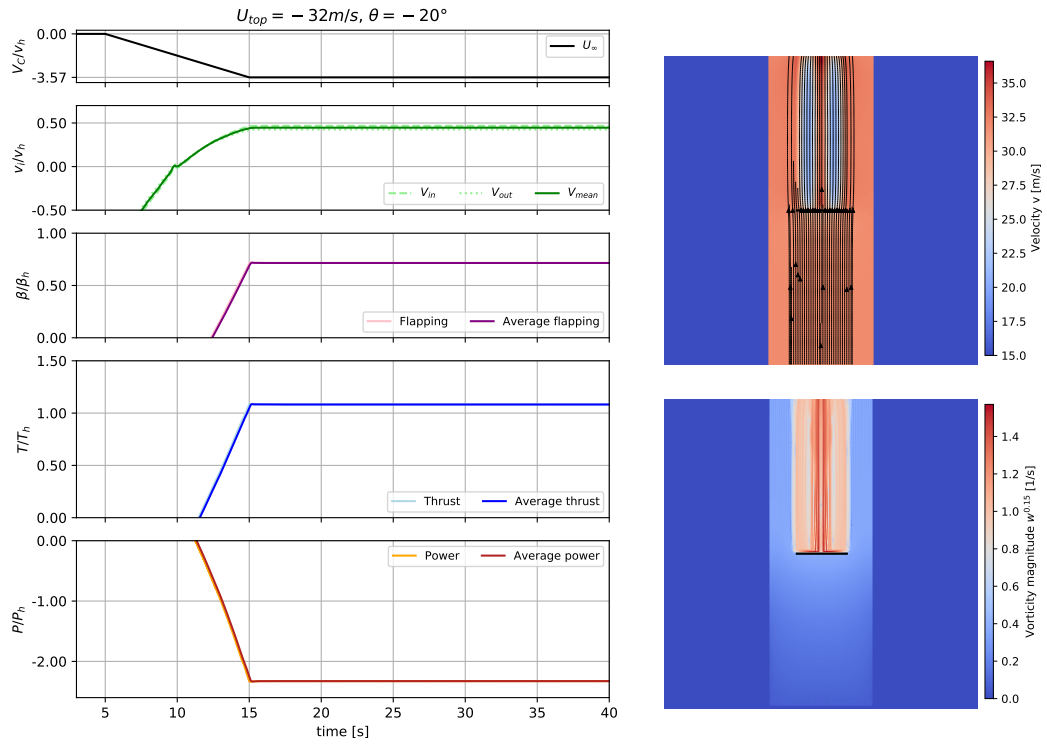


Figure 4.51: Simulation at $V_C + \epsilon_C = -24[\text{m s}^{-1}]$ with the adapted θ

Figure 4.52: Simulation at $V_C + \epsilon_C = -28 [\text{m s}^{-1}]$ with the adapted θ Figure 4.53: Simulation at $V_C + \epsilon_C = -32 [\text{m s}^{-1}]$ with the adapted θ

We can immediately tell that those simulations are far better. Indeed, one will notice that the power has become negative: the flow is now running the blades! Looking at figures 4.54 and 4.56 immediately show a way better fit. This proves that using a fixed pitch for all the simulations is only acceptable in a reduced range of descend rates, even using a correction factor.

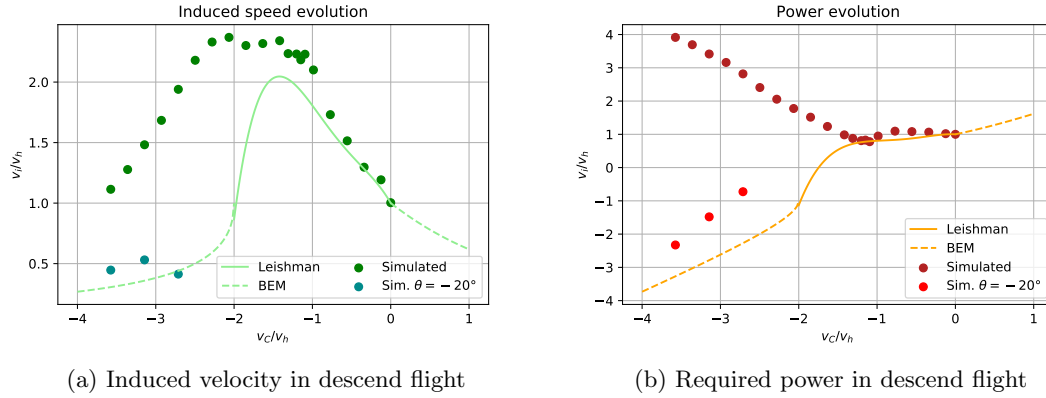


Figure 4.54: Comparisons of the simulations with the theoretic expectation

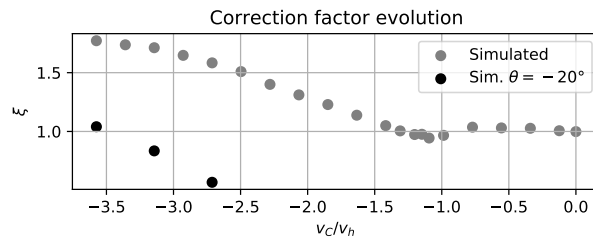


Figure 4.55: Thrust-based correction factors

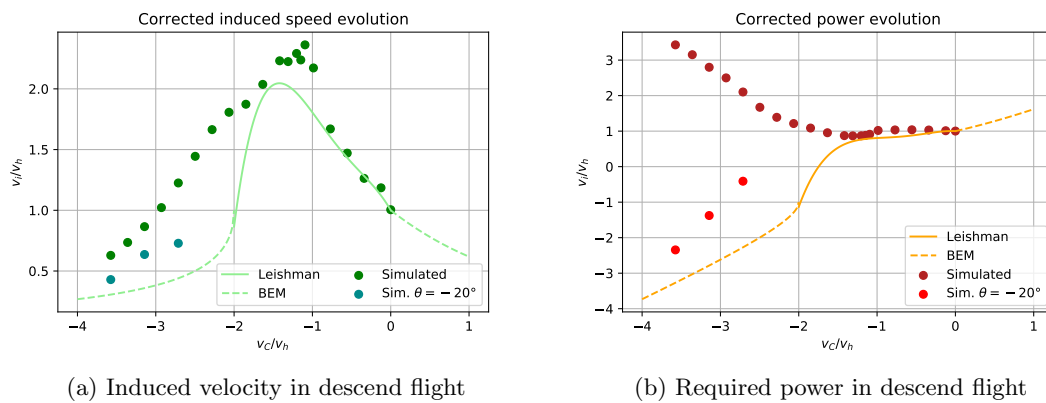


Figure 4.56: Corrected comparisons of the simulations with the theoretic expectation

Chapter 5

VRS analysis

The VRS is characterized by the fact that each blade goes in the wake of its predecessor. In other words, it happens when the descend rate matches the net induced flow (i.e. the flow that we can directly measure on the rotor plane $v_i + V_C$). A look at figure 5.1 shows that indeed, the VRS are starting when $V_C \simeq -v_{i,net}$ and stop when $V_C \simeq -1.5 v_{i,net}$. The reason why VRS survives when $V_C < -v_i$ is that the vortex ring is accelerating the upwards flow locally. This can be observed on figure 5.2¹

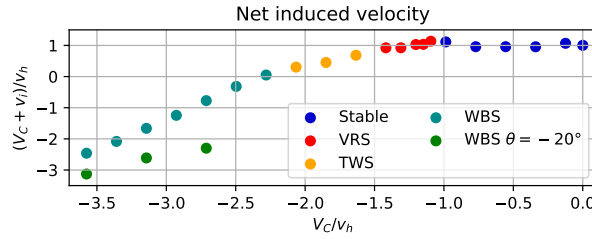


Figure 5.1: Net induced flow along the descend

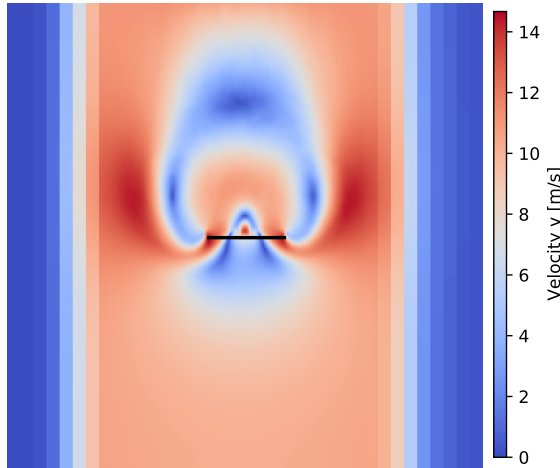


Figure 5.2: Time-average velocity field of the xz - and yz -planes combined at $V_C + \epsilon_C = -11 \text{ [m s}^{-1}\text{]}$ ($[70\text{s} - 130\text{s}]$, 40 measures/s (4800 data))

¹Note: it is exactly the same as figure 4.23a without the streamlines.

5.1 VRS entry

We will firstly look at what happens when VRS forms itself. If we look at every simulation that reaches it or goes through it, we can always see a kind of “peak”, where the thrust gets to $\sim 80\%$ of T_h or even less (it is viewable on every simulation starting from the one at -8 m/s and it particularly prominent at -11 and -12 m/s). A look at the instantaneous slices shows that it is the moment where the rotor plane “catches” the vortex ring. An illustration of this is proposed on figures 5.4 and 5.5 for the simulation at -11 m/s.

Looking at figure 5.3, we observe that the vortex ring is forming itself under rotor plane just before the drop (26-28s). During the thrust drop (28-31s), we can see it rising to the rotor plane. During the climb (31-36s), the vortex ring establishes itself on the rotor plane and after the rise (36-38s) it is in place: we are in VRS. It means that the thrust drop is due to the helicopter which is “falling” in the vortex. This leads to a sudden but short acceleration towards the ground in the same manner as what some people call “air holes” when an aircraft goes through turbulences. At the same moment, the blades are going down (the flapping is indeed, and quiet logically, directly linked to the thrust). We also see that the “calming down” of the blades vibrations happens at the very moment of the full establishment of the VRS.

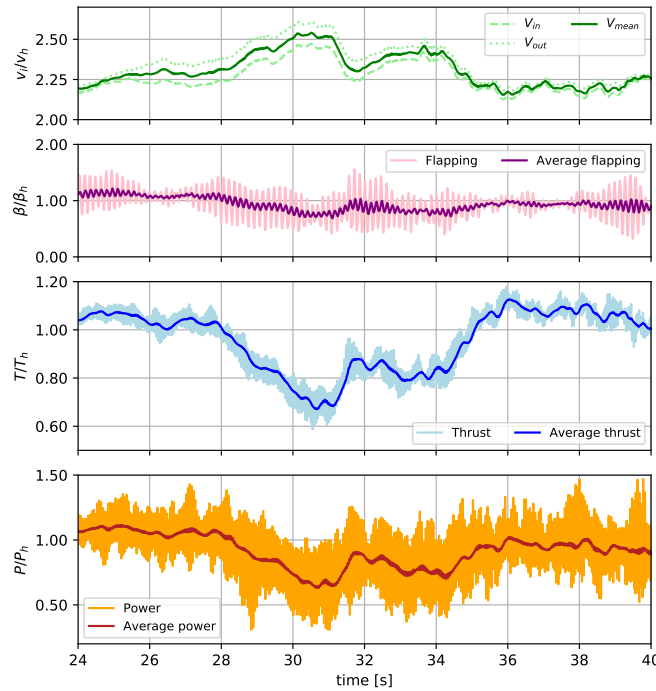
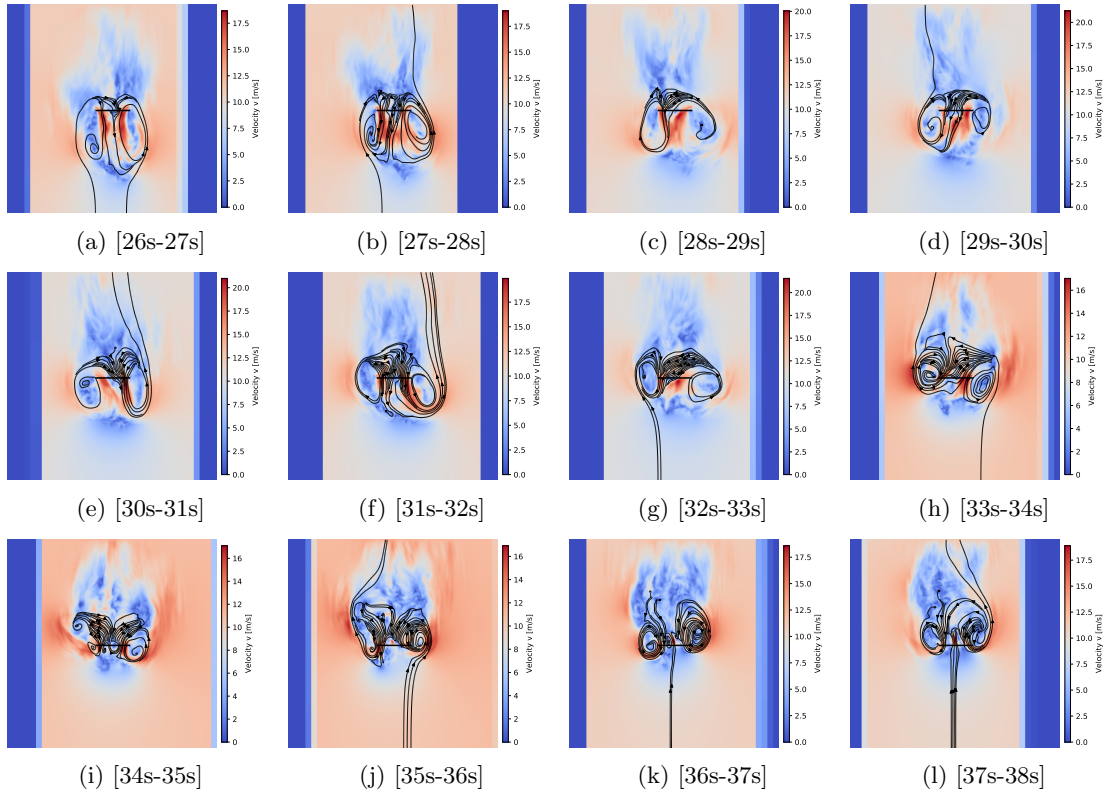
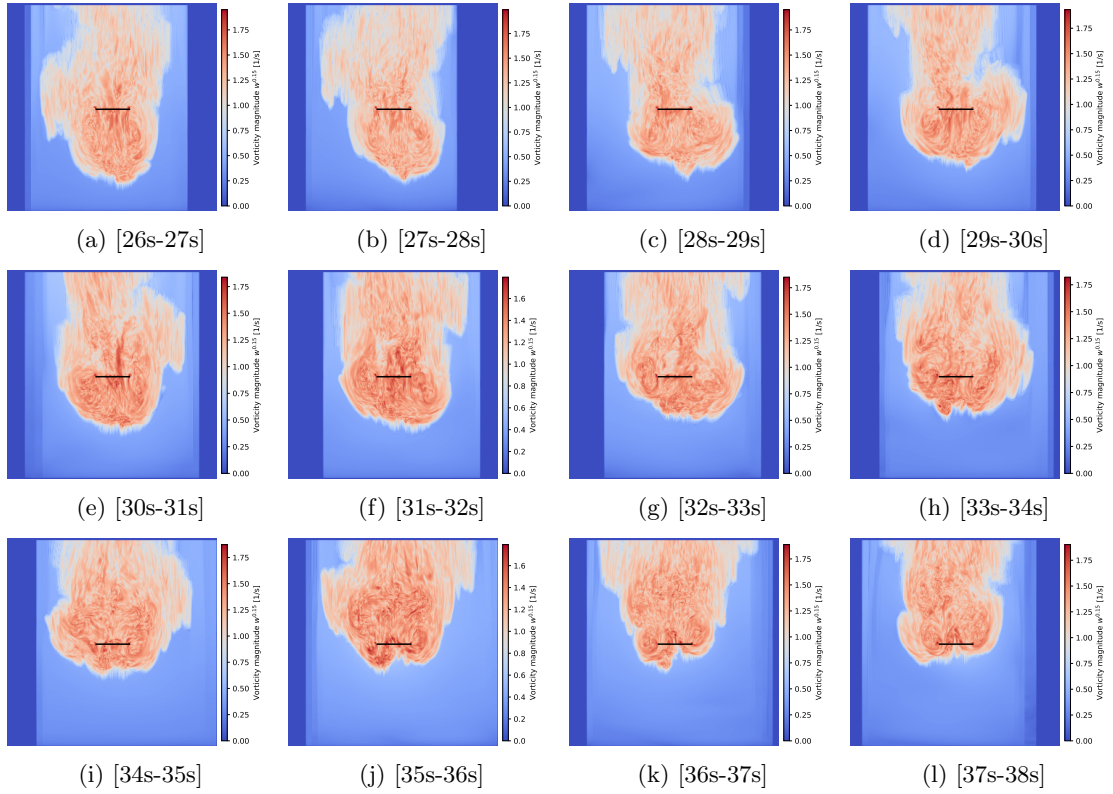


Figure 5.3: Zoom on the “peak” of the simulation at $V_C + \epsilon_C = -11$ [m s $^{-1}$]

Figure 5.4: Streamlines of the velocity evolution of the yz -plane at -11 m/s (40 measures/s)Figure 5.5: Vorticity evolution of the yz -plane at -11 m/s (40 measures/s)

5.2 VRS exit

Let's now look at how a vortex ring breaks into a turbulent wake. This time, the simulation at $U_{top} = -14[\text{m s}^{-1}]$ will be used for illustration. The zoom of the time window is on figure 5.6, the streamlines are on figure 5.7 and the vorticities are on figure 5.8. The VRS isn't hold very long here and its formation is more chaotic than previously. We can observe the final formation at 24s and the VRS between 25s and 26s. During the following second, we can see that the vortex ring is collapsing on the left-hand side but not on the right-hand side. It seems thus that the vortex ring isn't expelled entirely at once, but from one side first. From 27s, we see that some recirculations are generated here and there, but they don't form a vortex ring anymore. It is the turbulent wake state.

Looking at the curves, we see that, as before, the thrust is minimal when the VRS forms itself then rise again to a maxima. At the moment it collapses, we have a small lose of thrust again and once the vortex ring is completely gone, we nearly reach our maxima again, but we maintain it. This small bump is also followed by the power and the induced velocity.² The flapping is really the best indicator, it becomes wavy when the recirculations get to the rotor plane. Suddenly, it is smooth and at a minima during VRS, then it becomes wavy again and at a higher mean value.

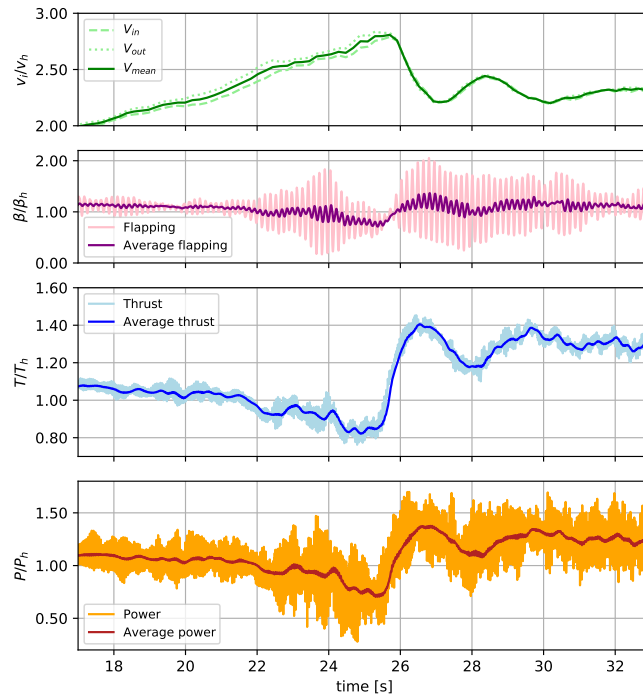
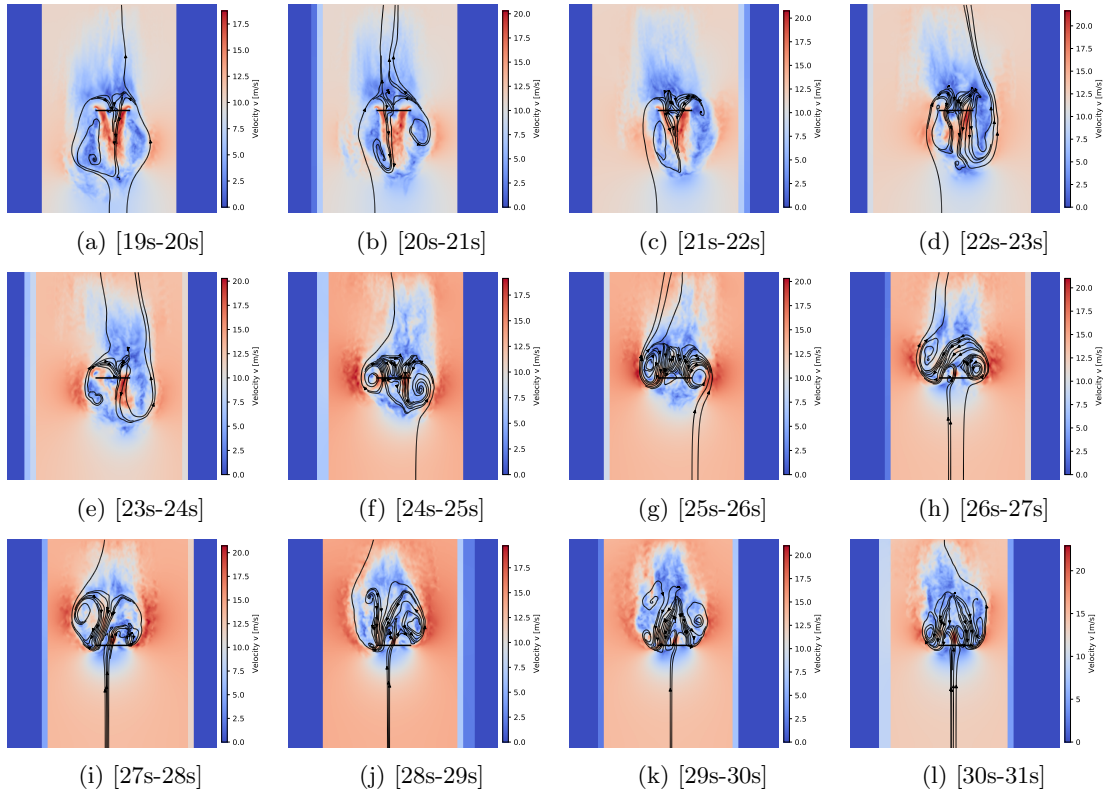
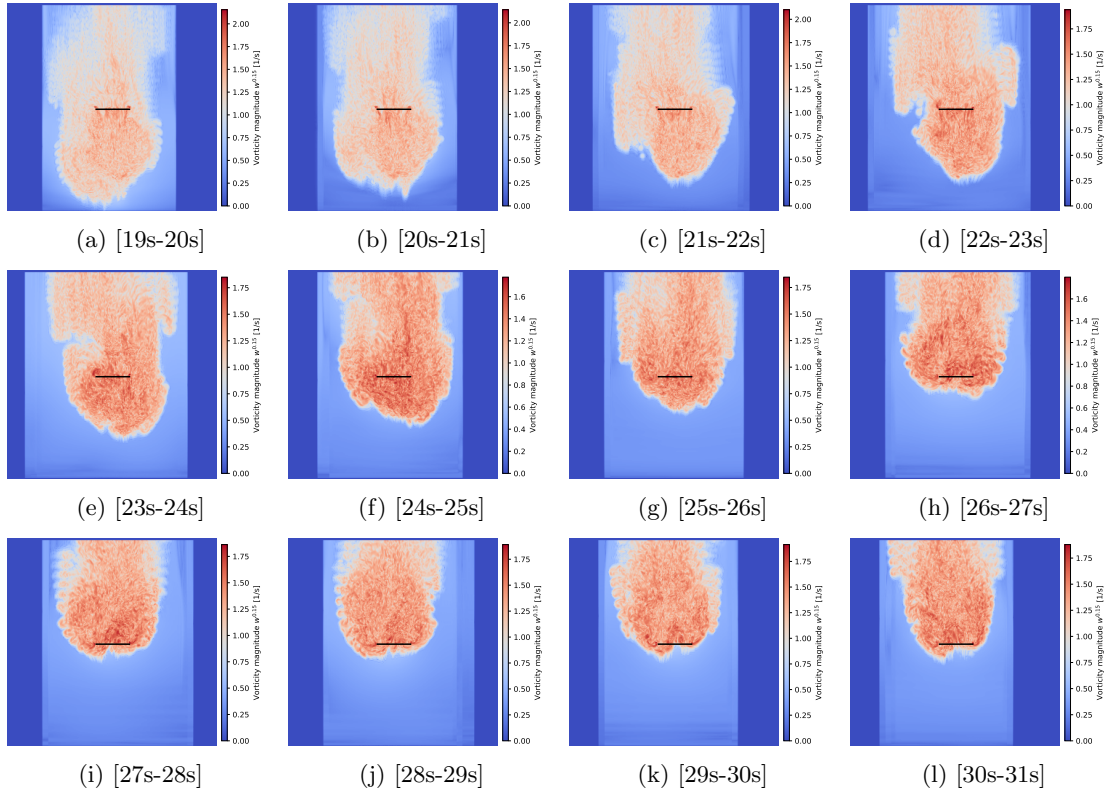


Figure 5.6: Zoom on the VRS passage of the simulation at $V_C + \epsilon_C = -14[\text{m s}^{-1}]$

²Note: the V_C ramp is finishing at 25s here, the induced speed must thus be ignored before that time.

Figure 5.7: Streamlines of the velocity evolution of the yz -plane at -14 m/s (5 measures/s)Figure 5.8: Streamlines of the velocity evolution of the yz -plane at -14 m/s (5 measures/s)

5.3 Future research prospects

The finalization of this thesis gives me more questions than answers. In particular, it would be interesting to be able to maintain our VRS longer. On the simulations presented in section 4.3, the streamlines were obtained using a very long time period. Showing those big and symmetrical vortex rings. But instantaneous frames show that in reality, the vortex rings are collapsing and reforming continuously. Is this the real behavior of the VRS or is it possible to keep a toroidal vortex ring around the blades longer than a few seconds ?

With our setup, the theoretic VRS looks like a transitory phenomenon, leading - at best - to a bigger vortex ring that goes very high above the helicopter. And for cause, the huge thrust fluctuations that we can observe are supposed to lead to successive accelerations and decelerations. But since we are working with a fixed rotor and fixed inflow velocity, those accelerations aren't happening. It would be interesting to look at what happens if we manage to make our rotor to move depending on the thrust it produces. To do so, a bigger box would probably be needed, asking for more computation power.

Another outlook can be to determine the impact of the number of blades. Where 3 blades are separated by an angle of 120° , letting some space between them, using 5 blades would reduce this angle to 72° . It is not forbidden to think that, with less space between the blades, the vortex ring would be maintained more easily. Indeed, since the induced speed isn't characterized by the number of blades, the vortices would be naturally closer from each other. Let's note that these kinds of analysis would also serve propeller airplanes, that can encounter VRS when they reverse thrust during landing.

The most important thing seems to be the ability to control the pitch efficiently. We saw that the pitch has to vary before it gets to WBS, it means that intermediate pitches have to exist in VRS and TWS. It is also said that adding collective while being in VRS would make it even worse, is this the key to maintain the VRS ?

Conclusion

The goal of this thesis was to study how helicopters behave in VRS. The first thing I had to do was to simulate hover as best as possible, it is the starting point of a descend and a well know regime, helping to make valid comparisons. We have seen that the model could be limited by its mesh which, being composed of cubes, would align himself with our 4 blades, leading to potential integration errors. Those errors were responsible for a very unsteady thrust, in a regime that is supposed to be stable. To avoid that potential problem, the model had to be modified in order to have an odd number of blades. At that moment, all the reference data had to be redetermined and compared to the real helicopter we where simulating: the H-135.

That done, I could attack the real stuff. I firstly tried to chase VRS directly but it was inefficient, forcing me to use the methodology that was presented in chapter 4. This methodology was: starting from hover, go to different descend rates, one at a time, until VRS is reached. To avoid problems due to to slowness of the controller, this had to be done with a fixed pitch: the one of the hover. Once VRS were reached, the simulations corresponding to them were greatly expanded, with a lot of measurements, permitting big datasets that are statistically good enough to generalize. In addition to that, the decision was taken to go beyond VRS, in order to see what would happen at very high descend rates and to plot the induced velocity graph, giving an even better comparison point. The fixed pitch approach showed here its limit: it cannot do an acceptable WBS, but more something like a heavy braking. To complete the graphs, simulations with a different pitch were done, giving satisfying results.

The most interesting part was yet to come: the analysis of how VRS forms and what are their warning signs. We observe that the VRS begins with a drop of thrust. It is the exact moment where the vortex “climb” on the rotor plane, the thrust then rise again and VRS is initiated. Eventually, the vortex ring gets bigger and loses his toroidal form. If the descend rate is high enough, the vortex ring collapses, resulting in a new loss of thrust, rapidly recovered, leading to the turbulent wake state. Before getting to this point, the helicopter is in a less and less stable behavior. Here are our warning signs:

- The whole helicopter begins to vibrate, and especially the blades;
- The power is being reduced: the vortex helps keeping the same induced velocity;
- The thrust is dropping, giving the impression of falling.

Every pilot that encounters one or more of these signs should immediately stops his descend. Otherwise, the VRS will arrive just after. The signs we are in VRS are:

- Less vibrations on the blades;
- A very unsteady thrust, leading to tremors.

In this condition, the pilot should immediately make an escape maneuver like a Vuichard.

Via this thesis, I expect having helped a better comprehension of this under-researched subject. I leave it with the door open to other improvements in the study of air-safety.

Appendix A

Model description

A.1 MBS joints of the model

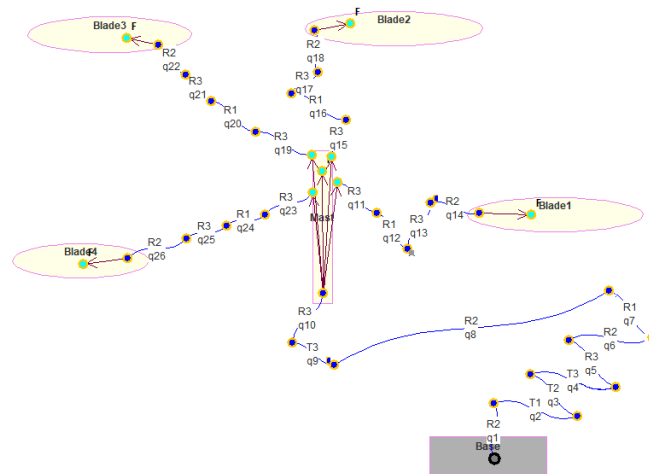


Figure A.1: Robotran model of the H135

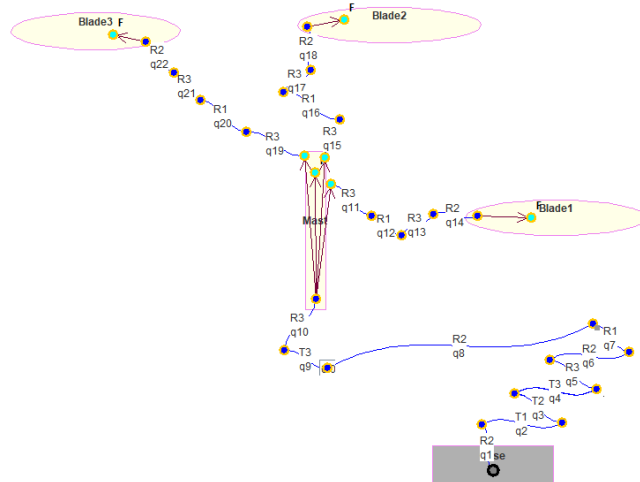


Figure A.2: Robotran model of a 3 blades H135

Starting from the base, we have:

- q_1 **R2** a rotation that permit to turn the whole model for an easier implementation in VPM;
- q_2 **T1: BODY_FWD** the translation degree of freedom in the x axis, or *forward motion*;
- q_3 **T2: BODY_LAT** the translation degree of freedom in the y axis, or *lateral motion*;
- q_4 **T3: BODY_UP** the translation degree of freedom in the z axis, or *up motion*;
- q_5 **R3: BODY_HDG** the rotation degree of freedom around the z axis, or *heading motion*;
- q_6 **R2: BODY_PITCH** the rotation degree of freedom around the y axis, or *pitch motion*;
- q_7 **R1: BODY_ROLL** the rotation degree of freedom around the x axis, or *roll motion*;
- q_8 **R2: MAST_PITCH** a rotation that permit to incline the rotor towards the front;
- q_9 **T3: MAST_THR** a translation that permit to discard the rotor hub from the cell;
- q_{10} **R3: MAST_ROLL** the rotor axial rotation;

Then for each of the blades:

- q_{11+k} **R3: BLADEi_AZM** the blade azimuth angle ψ_i ;
- q_{12+k} **R1: BLADEi_FLAP** the blade flapping angle β_i ;
- q_{13+k} **R2: BLADEi_LLAG** the blade leading/lagging angle ζ_i ;
- q_{14+k} **R1: BLADEi_PITCH** the blade pitch angle θ_i ;

With $k = \{0, 4, 8, 12\}$.

A.2 Airbus helicopter H125

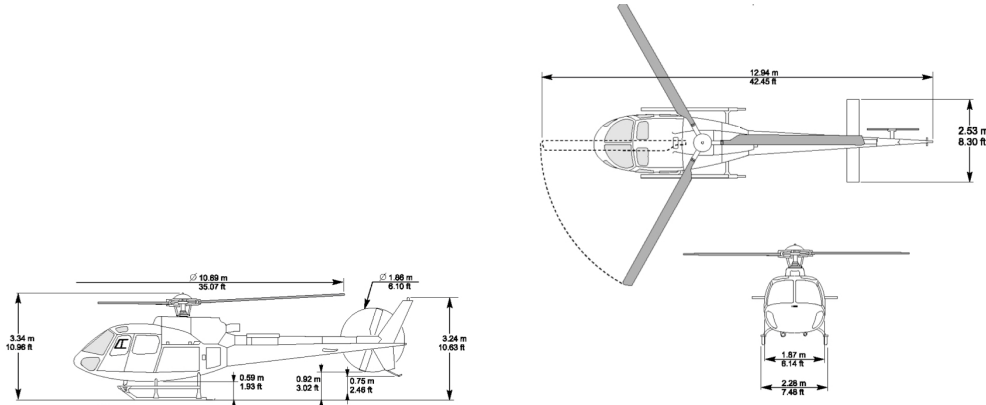


Figure A.3: Airbus Helicopter H125

©Airbus

Appendix B

Descend flight

B.1 3D wakes for the descend flight

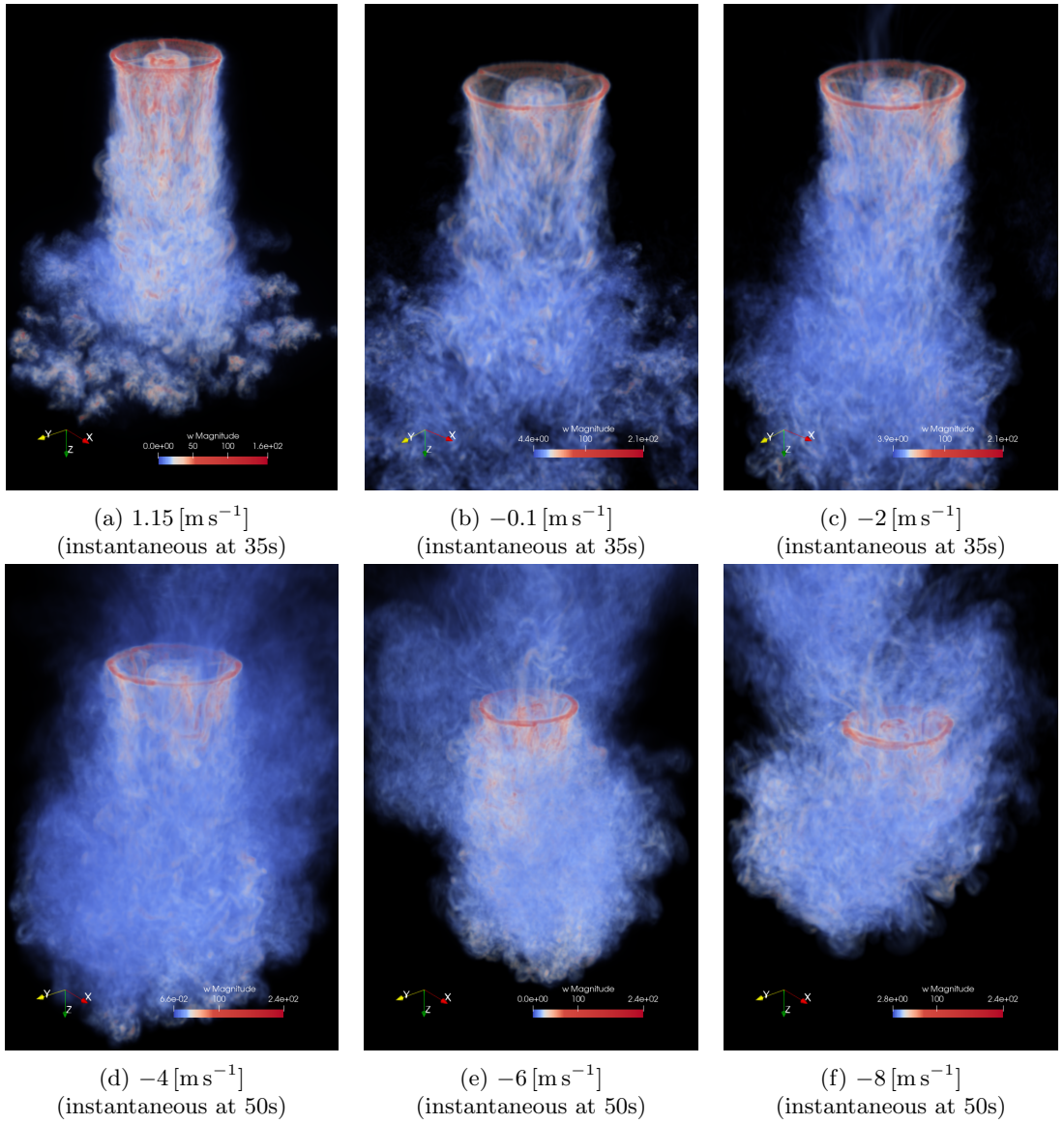


Figure B.1: 3D wakes

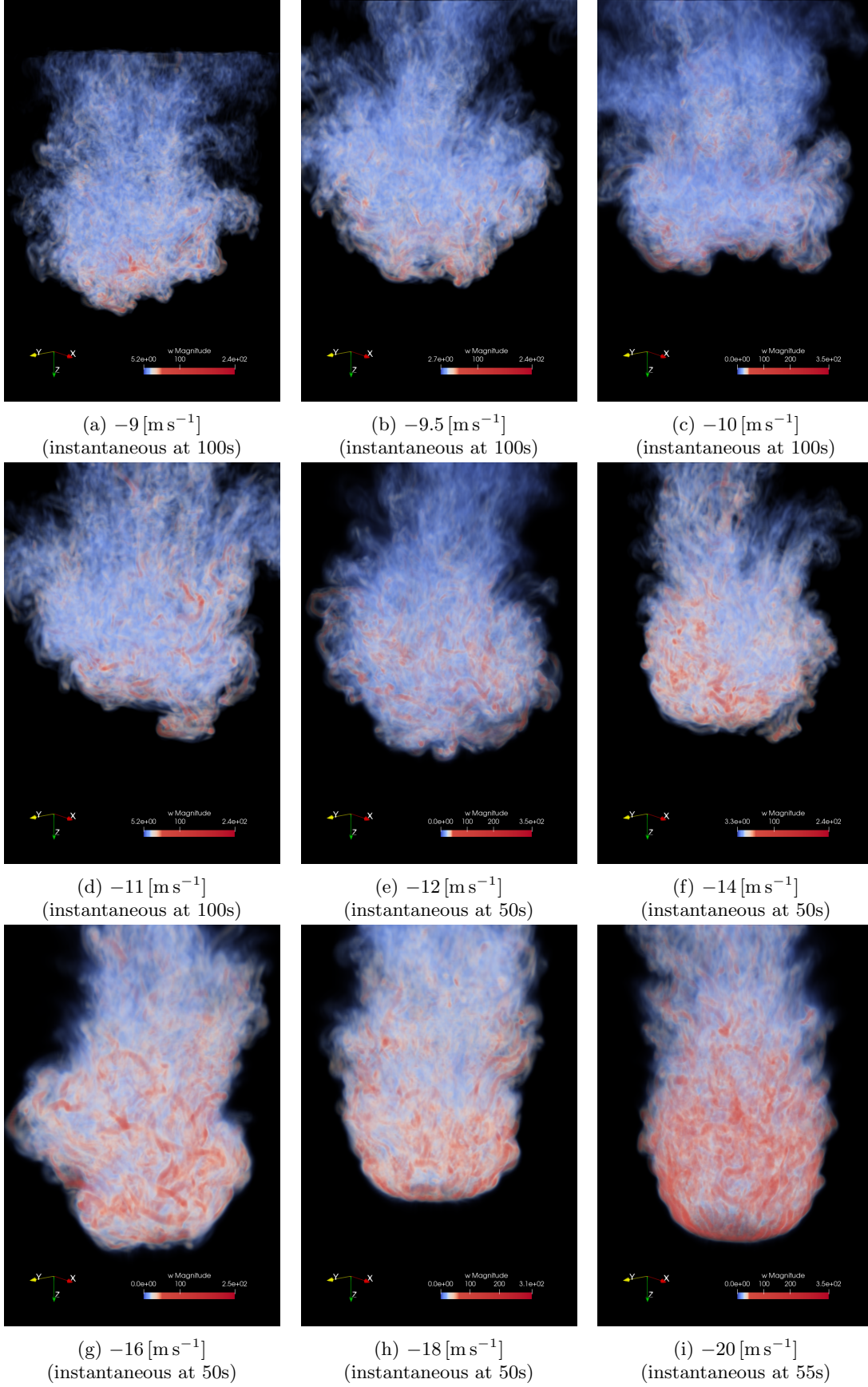


Figure B.2: 3D wakes

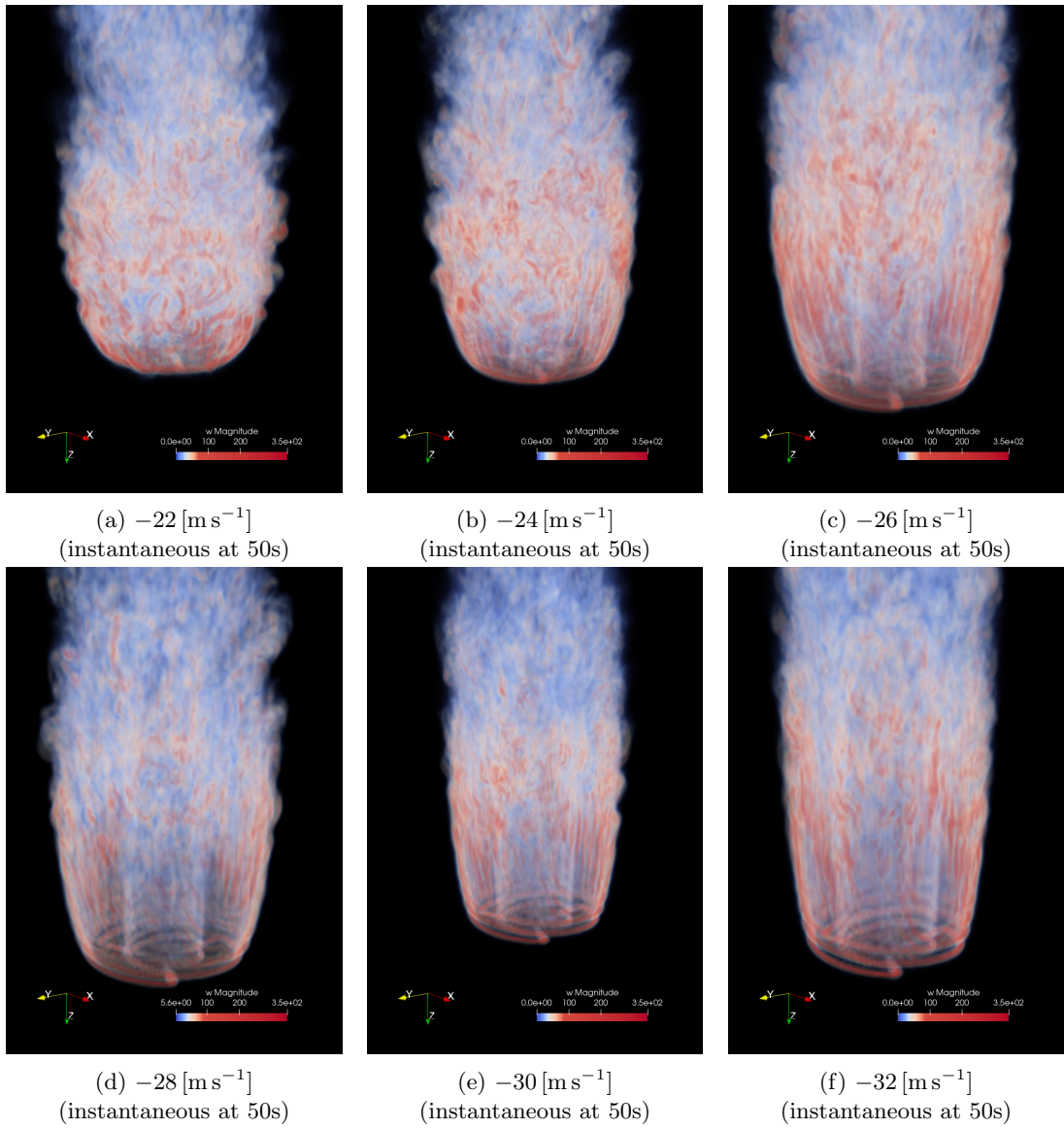


Figure B.3: 3D wakes

B.2 3D wakes with the adapted pitch

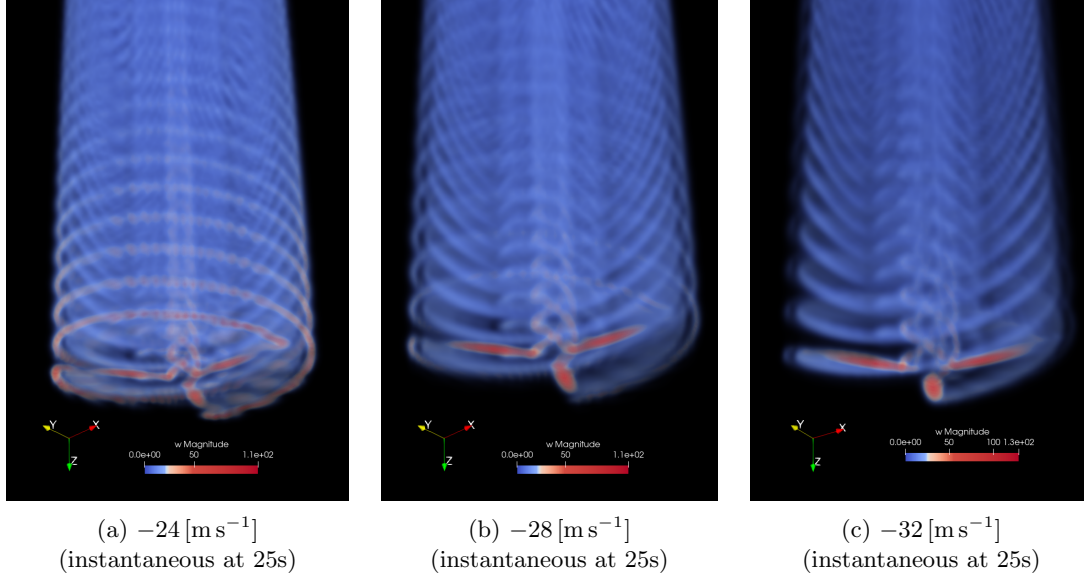


Figure B.4: 3D wakes of the windmill state with $\theta = -20[^\circ]$

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UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain

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